University of Alberta

Response of carabid assemblages to genetically modified herbicide-tolerant corn and to some sustainable farming practices

by

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Abstract

In agricultural lands, predation of arthropod pests by natural enemies provides a tool for the development of farming strategies that rely less on insecticides. The Carabidae is a speciose family of beetles that constitute a large portion of these natural enemies and are known to be affected by farming practices. To investigate the impact of new farming practices on carabid assemblages, I used pitfall traps throughout the growing season in 1) experimental plots of conventional and genetically modified herbicide-tolerant (GMHT) corn under continuous and rotation regimes and 2) experimental plots of a rotation of wheat, potato and bean under sustainable and conventional farming practices. GMHT corn had a significant influence on the carabid assemblages in one of the two years investigated. It was associated with reduced activity density of the dominant species, *Bembidion quadrimaculatum*. Higher mid-season weed density in plots with GMHT corn is likely to explain these results. Rotation of corn with canola increased the activity density, lowered the diversity and modified the carabid community structure. Sustainable farming increased the activity density of carabids but did not increase diversity or significantly change the community structure. However, click beetle populations, which are potential pests, were also enhanced under sustainable farming. Many carabid species were associated with different crops which affected the year to year variation on community structure.

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1. Chapter 1 - Introduction

1.1. Insects in agriculture

Most of what is known about insects in agricultural systems is about those species that cause significant economic loss. On the Canadian prairies, for example, insect pests cause more than 200 M dollars of crop damage annually (Dr. Cárcamo personal communication). Insect pests are studied extensively with the hope that a better understanding of their biology will lead to farming strategies that minimize insect crop damage. Although pesticides may be used to control insect pests effectively, various side effects may result from their application. Frequent pesticide applications, for example, have led to soil and water contamination, development of insecticide resistance in certain insects and negative effects on populations of non-target organisms (Pimentel and Edwards 1982). Many non-target organisms perform essential services in agriculture that may go unnoticed until the organisms are missing. For instance, the emergence of a secondary insect pest following pesticide applications can result from reduction in population size of beneficial insects that under normal circumstances were able to control the population density of the pest insect. Among beneficial insects, the ground beetles (Coleoptera: Carabidae) comprise a large family of beetles common and abundant in agricultural land.

1.2. Carabidae

The Carabidae is a speciose family with more than 900 species recorded in Canada (Lindroth 1961-1969). Adults of the various carabid species range in size from 1.5 mm to 30 mm (in Canada) and are mostly nocturnal but some species are diurnal. Most carabid species are considered generalist carnivores or omnivors but many specialisations are observed. For instance, species in the genus *Calosoma*, called "caterpillar hunters", prey predominantly on lepidopteran larvae. For that reason, *Calosoma sycophanta* L. was introduced into eastern USA forests to control populations of gypsy moth (*Lymantria dispar* L.), an important exotic tree defoliator. Members of the tribe Cychrini have developed a narrow and elongated head to specially feed on shelled organisms such as snails. Others species like those in the genera *Notiophilus* or *Loricera* are collembolan specialists. *Loricera pilicornis* (Fabricius 1775) has adaptations on its antennae to capture and hold collembollans. Other species are also known to be predominantly granivorous. Species in the genus *Amara* or *Harpalus*, for example, prefer seeds from plant in the *Brassicaceae* and *Apiaceae* respectively (Thiele 1977). Carabid larvae of the genus *Nebria* detect their prey using tactile setae located on their head capsules and on their bodies. Once a prey is detected, a larva orients itself toward the prey and its contact with specialized nasal spines and (or) hairs extending from the frontal corner triggers a rapid contraction of the mandibles around the prey (Spence and Sutcliffe 1982).

Many carabid species are strongly associated with particular habitats, while others are more flexible. For that reason, many researchers have promoted carabids as an indicator group for environmental change (Rainio and Niemela 2003) because they are widely distributed, abundant, speciose and easy to collect and identify. Also, analysis of environmental impacts is facilitated by the fact that the biology of many species is known to a certain extent. Carabids are a significant fraction of soil-dwelling insects in northern Canadian farms, and along with the spiders (Araneae) and rove beetles (Coleoptera: Staphylinidae), constitute the vast majority of the epigaeic fauna (Goulet 2003). It is not uncommon to find between 30 and 60 carabid species in an agricultural field, which can represent approximately 20 percent of the surrounding fauna (Goulet 2003). Being diverse, abundant and predominantly carnivorous, carabids are mostly considered beneficial in agriculture. They have been reported to prey on many agricultural pests (Frank 1971, Grafius and Warner 1989, Floate et al. 1990).

1.3. Sampling Carabids

The most common technique used to assess the abundance of carabids within a certain location is by pitfall trapping (Spence & Niemelä 1994). Pitfall trapping gives a blended measure of density and activity of carabids rather than absolute abundance. This is mainly due to the fact that larger carabid species moves faster and farther than those that are smaller bodied and therefore larger individuals have an increased chance of capture. Therefore, throughout this document, I refer to the carabid abundance as "activity density".

1.4. Carabids and Agricultural Pests

Arthropod prey of carabids are varied and numerous and include Lepidoptera (Frank 1971, Brust et al. 1986), Hemiptera (Hance 1987, Winder 1990), Coleoptera (Tyler and Ellis 1979), Diptera (Grafius and Warner 1989, Floate et al. 1990) and other orders (Holland 2002). Although some species of carabids have been occasionally reported as pests in specific situations (Thiele 1977, Luff 1987, Larochelle 1990), the generally beneficial role of carabids is widely accepted. Carabids, depending on their body size, can consume a large amount of food. For instance, *Bembidion quadrimaculatum* (L.1769) (3-4 mm) was reported to eat as many as 25 onion maggot eggs per day (Grafius and Warner 1989). A larger carabid, *Pterostichus cupreus* (11-13 mm), ate as many as 125 apterous cereal aphids per day (Chiverton 1988). In addition, Cárcamo and Spence (1994) reported that the number of prey taken is inversely proportional to prey size, in other words the larger the prey item is, the fewer will be consumed by a carabid.

It is logical to think that predator density plays an important role in maintaining low pest populations. Menalled et al. (1999) reported an increase in removal of prey items when carabid populations were experimentally augmented. Similarily, predator density can be an important factor in reducing aphid populations (Hance 1987). Thus, the ability of a carabid assemblage to restrain pest populations in agriculture settings is greater with increasing population size and depends on the mix of body sizes included.

Since carabid species have different phenologies and feeding preferences, maintaining carabid diversity could be important to maintain significant predation on a wide variety of potential pests throughout the season. The majority of work done on carabids in agriculture has focused on the impact of farming practices on their assemblages. With the ongoing pressure to make agriculture sustainable, understanding how farming practices affect carabids and other generalist predators may be an important step in developing pest management strategies that depend less on pesticides and more on natural predators.

1.5. Effects of Farming Practices on Carabid Assemblages

Agriculture is an intensive operation that disturbs the soil structure and its physical properties as well as the vegetation it supports. Therefore, carabids that spend most of their lives on or in the soil are highly susceptible to the impact of agricultural practices. The following paragraphs describe only few practices that have been demonstrated to affect carabid assemblages. More in-depth discussions of some agricultural impacts on carabid assemblages are presented in chapters two and three.

1.5.1. Effects of undisturbed area

Recent work has focused on developing weedy/grassy refuge areas where assemblages of natural enemies of agricultural pest insects (including carabids) could be enhanced. Higher carabid activity density and diversity has often been reported in fields bordered or divided by weedy/grassy strips, compared to fields without such structures, and this emphasizes the importance of undisturbed areas for carabid communities (Doane 1981, Hassall et al. 1992, Lys and Nentwig 1992, Lys et al. 1994). In most cases, dense and complex vegetation provides good breeding and overwintering sites for carabids. Although, there is no strong evidence that the economic cost of losing cultivable land is offset by the beneficial action of leaving such refuge structures for predators, long term effects of such structures may be important in faune conservation and other contexts. In fact, such unexploited areas also provide windbreaks to prevent soil erosion, run-off buffer zones and nesting and foraging sites for farmland wildlife (Holland 2002).

1.5.2. Effects of tillage

Tillage has been often used to manage crop residue, incorporate organic matter in the soil and control weeds and arthropod pests (Musick 1987, Holland 2002). However, more sustainable practices recommend a reduction or absence of tillage when possible as it causes soil erosion. Tillage reduction can also benefit carabid assemblages because generally, deep tillage reduces carabid diversity and abundance (Kromp 1999). Although some studies found no effect of tillage on the overall carabid activity density (Cárcamo et al. 1995, Hummel et al. 2002),others have reported higher activity density and diversity in farming systems under no or low tillage regimes (House and Stinner 1983, Ferguson and McPherson 1985, Andersen 1999).

1.5.3. Effects of crop types

Crop type influences carabid assemblages by providing different canopy structures and plant densities. Open canopy are generally associated with drier and warmer soil than are closed canopies and this difference influences the composition of carabid assemblages according to species habitat requirements. For instance, Ellsbury et al. (1998) reported that *Poecilus* (*Pterostichus*) *lucublandus* (Say 1823) predominates in wheat while *Cyclotrachelus alternans* (Casey 1920) dominated in corn and alfalfa grown nearby. Butts et al. (2003) reported that crop types influenced carabid assemblages. In this study, monocultures of peas or canola yielded more carabids than when either were intercropped with barley, although the authors suggested that intercropping canola and peas is likely to increase carabid activity density. Also, crops that mature early and maintains good vegetal ground cover are more likely to maintain higher carabid diversity (Holland 2002).

1.5.4. Effects of pesticides

Insecticide application also greatly influences carabid assemblages. After application of lindane insecticide (organochlorine) carabid population density dropped and took 2 months to recover to original density (Sekulic et al. 1987). As mentioned by the authors, the study was done on relatively small experimental plots (up to 10 ha) and thus the recovery time may have been shorter than what is expected from regular farm size. Although augmented activity density of some species following insecticide application has been reported (Thornhill and Edwards 1985), most insecticide application is toxic to carabid beetles (Mowat and Coaker 1967, Edwards and Thompson 1975). Testing the effect of different insecticides on two carabid species, *Bembidion quadrimaculatum* and *Bembidion obscurellum*, Floate et al. (1989) found that carbofuran and chloropyrifos was the most toxic of the tested insecticides, causing respectively 83 and 100% mortality.

Generally, the effects of herbicide on carabid assemblages is indirect via habitat modification. Four herbicides were tested on carabid beetle assemblages but none showed any toxic effect (Brust 1990). However, removal of weeds can change the micro-climatic conditions experienced by carabids in the field, as well as reduce the number of food items available (Chiverton and Sotherton 1991). Also, removal of weeds may expose the beetles to potential predators such as birds.

1.6. Objectives of the Thesis

The main objective of this study is to investigate the responses of carabid beetles to several farming practices that are gaining popularity in western Canada. In Chapter 2, I compare the responses of carabid assemblages to two different corn varieties grown under two different cultivation regimes. The influence of the genetically modified herbicide-tolerant corn variety (GMHT) is compared to that of the conventional corn variety both under a continuous or rotation regime. A significant agronomic difference between the corn varieties is the type of herbicide applied to each and the efficiency of the variety-herbicide combination in controlling weeds. I hypothesized that GMHT corn plots would have a lower weed density than the conventional plots and that this would, in turn, reduce carabid activity density and diversity and alter the species composition of the carabid assemblages. Carabid assemblages are also compared between continuous corn and corn rotated with canola to test the hypothesis that rotation will increase both carabid diversity and abundance.

Chapter 3 compares the responses of carabid assemblages between sustainable and conventional farming in a rotation of wheat, beans and potatoes. 'Sustainable' practices differed from those considered 'conventional' by using direct seeding or reduced tillage where possible, fall-seeded cover crops in wheat and beans, composted cattle manure as a substitute for inorganic fertilizer and higher plant density in the bean crop. I hypothesized that different crop types will influence carabid species composition and that fields grown under the sustainable treatment will have a greater carabid activity density and diversity than those grown under conventional treatment.

Chapter 4 presents a general discussion and synthesis to integrate the results of the data-oriented chapters in the context of pest management and sustainable farming. The general discussion provides a perspective for current farming practices in Alberta and underscores the important role of the carabid beetle populations and those of other generalist predators in providing inexpensive pest control.

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2. Chapter 2 - Title

Comparison of Genetically Modified Herbicide-Tolerant *vs.* Conventional Corn Varieties: Impact on Carabid Beetle Diversity, Community Structure and Activity Density

2.1. Introduction

Weeds are a major constraint on agricultural yield; however, weeds also support biodiversity within agricultural systems and may be associated with other agricultural advantages (Marshall et al. 2003). For instance, some general herbivorous insects may prefer to eat weeds instead of the crop. Also, the presence of weeds may enhance populations of beneficial insects such as carabids by providing shelter against weather variation, diversifying micro-habitat structure and increasing food (Purvis and Curry 1984, Holland 2002). Therefore, weed removal by herbicides or cultivation can affect carabid communities and their beneficial actions. Generally, the presence of weeds within or in the margins of a field increases carabid abundance and diversity (Speight and Lawton 1976, Hassall et al. 1992, Lys and Nentwig 1992, Lys et al. 1994, Pavuk et al. 1997, Ellsbury et al. 1998, Andersen and Eltun 2000), although a few studies have reported no effect of weeds on overall carabid abundance (Purvis and Curry 1984, Chiverton and Sotherton 1991). Speight and Lawton (1976) found a higher capture rate of carabids in areas where meadow grass (*Poa annua* L.) was present within a wheat field (*Triticum aestivum* L). They also observed higher predation on fly pupae by carabids in these areas, which link weeds to enhanced predation rates. The response of carabids to vegetation cover differs among species, however, suggesting that species-specific responses to weeds are the rule (Barney et al. 1984, Armstrong and McKinlay 1997, Pavuk et al. 1997).

Crop rotations are routinely used as a sustainable methods to reduce the risk of diseases and pest outbreaks but also to prevent the exhaustion of soil nutrients (Glen 2000). However, crop rotation for weed management will expose carabids to a different canopy structure and different farming operations every year and this will affect their assemblages. For instance, Hance et al. (1990) showed that crop type influences the activity density of carabids, and rotation affected many species, especially the spring breeders that are active at times of intense farming operations. Purvis and Curry (1984) also found that many species were affected by rotation and the cultivation period required for the crop

The increasing use of herbicides has lowered the need for both tillage and crop rotation to control weeds (Freemark and Boutin 1995). However, this change has negative effects on non-target fauna: many studies suggest a reduction of carabid activity under herbicide-treated crops (Boiteau 1984, Powell et al. 1985, Bitzer et al. 2002), and some reported the importance of species-specific responses given the diversity of carabid life histories (Pavuk et al. 1997). Herbicide toxicity was reported to affect carabids (Thiele 1977, Boiteau 1984) while other studies reported no toxic effect (Brust 1990).

The recent development of genetically modified herbicide-tolerant (GMHT) crop varieties offers a new tool for weed management. To this date, corn (*Zea mays* L.) soybean (*Glyciae max* [L.] Merr.) and canola (*Brassica napus* L.) are registered GMHT crops in Canada. Concerns have been expressed regarding the long-term effect of GMHT crops on biodiversity. For instance, Watkinson (2000) predicted a dramatic reduction in the number of weeds with wide adoption of GMHTs, which may potentially affect the survival of some seed-eating birds. However, Hawes et al. (2003) and Brooks et al. (2003) reported no effect of GMHT and conventional crops on the predatory response of carabids and spiders, but variations in activity densities were observed among species. On the other hand, using a suction-sampling approach, Haughton et al. (2003) found no difference in carabid response to conventional or GMHT corn, beet (*Beta vulgaris* L.) and oilseed rape. In their study, carabids were more abundant in GMHT than conventional corn only in one sampling date (August). Furthermore, Dewar et al. (2003) argued that it is possible to creatively use GMHT crops to enhance both weed and insect populations without compromising yield. Given the lack of direct evidence on the functioning of such approaches, it is crucial to study the long-term effects of GMHT crop varieties on non-target organisms as the use of these crops increases.

In this chapter, I investigate the diversity, community structure and activity density responses of carabids to two corn varieties: GMHT and Conventional, under continuous monoculture and rotation. I use the term 'corn variety' to refer to the herbicide-use associated with these two, i.e., to distinguish between the type of herbicide applied and its efficiency in controlling weeds. 'Continuous' is used to describe corn grown each year without rotation with other crops while rotation describes a corn crop that followed canola in the previous year. I hypothesised that 1) plots under corn rotation would host higher carabid diversity, different species composition and higher activity density than plots continuously grown with corn, 2) that GMHT corn would produce lower carabid activity density and diversity, compared to the conventional variety and 3) the response of carabid species to weed abundance would differ according to their body size. I predicted that larger carabids would be more restrained in their movements under high weed abundance and should be captured more often under lower weed abundance. One of the main difference sbetween continuous and rotation corn is a higher amount of residue left at the soil surface in the latter.

2.2. Materials and Methods

2.2.1. Site description and agronomic treatments

This study was conducted at the Fairfield research site (49°42'36 N, 112°42'32 W) of Agriculture and Agri-Food Canada, 10 km east of Lethbridge, Alberta, Canada, a region of dark brown chernozemic soil in the moist grassland ecozone of Southern Alberta. The investigation was part of a larger study on the environmental impacts of genetically modified corn and canola, which comprised 4 replicates of 19 plots (15 m x 35 m) arranged in a randomized block design (Figure 1). The plots were 3 m apart, and blocks were separated by 20 m of plowed soil in 2004 and mowed fall rye (*Secale cereale* L.) in 2005. Four treatments were selected for this study (Table 1). Disc cultivation followed by liver rod cultivation and harrow packing (2005) was performed prior to seeding for all treatments except the GMHT variety that was sprayed with glyphosate (Roundup®) before seeding. Fertilization was achieved with 34-17-00 NPK (235 kg/ha) with an additional 34-00-00 NPK (60 kg/ha) in 2005 only. Both corn varieties were seeded (75,000 plants/ha) in rows 75 cm apart on 28 May both years. Herbicides were applied according to manufacturers' instructions (Table 1). Irrigation of the entire study field was applied as needed. In 2005, flooding with 250 mm of rain in early June caused high corn mortality and plots were sprayed with Poast Ultra (Sethoxynil) at 300 ml/acre and Pardner (Bromoxinyl) at 500 ml/acre on June 24th to kill all corn. Corn was reseeded on June 25th but the chemical residue lowered corn emergence. Treatments were still applied as planned despite the resulting low corn density.

2.2.2. Sampling

2.2.2.1. Carabids

Carabids were sampled using two pitfall traps placed 10 m into each plot from both ends, near the mid line leaving *c.* 15 m between traps (Figure 1). Sampling periods were: 3 May to 30 Sept in 2004 and 18 April to 1 Sept in 2005. Each pitfall trap consisted of a 1 L plastic sleeve, dug into the ground flush with soil surface, and an inserted 0.5 L trap cup (11 cm in diameter)(Spence and Niemelä 1994) with 0.3 L of propylene glycol as a preservative. A plastic lid was placed 2 cm above each pitfall to prevent flooding and debris from entering the trap, and to reduce evaporation. Pitfall traps were emptied every 7 – 14 days. The contents of each trap were sieved through cheese cloth, preserved in 70% ethanol and refrigerated until processed. The main arthropod groups (Carabidae, Staphylinidae and Araneae) were separated and stored in 70% ethanol. Carabids were identified to species using the keys (Lindroth 1961-1969) and the reference collection at the Strickland Entomolgical Museum of the University of Alberta. Voucher collections were deposited at the Spence Laboratory Insect Collection of the University of Alberta, Edmonton, Alberta, Canada, and at the insect collection of the Agriculture and Agri-food Canada Lethbridge Research Centre, Lethbridge, Alberta, Canada.

2.2.2.2. Weed density and percent coverage

Weed density in each plot was estimated in 2004 by recording the number of each weed species found in each of 15, 0.25 m^2 quadrates that were distributed on each plot in an inverted "W" fashion at pre-seeding (May), pre-herbicide (June) and post-herbicide (July). In 2005, only the pre-seeding survey was done, but it was supplemented by an estimate of percent weed coverage, done on 29 July by taking five pictures of 1 m^2 quadrats arranged in a cross pattern in each plot. Using Image Pro Plus software, weed percent coverage was calculated by isolating the green color pixels and dividing the value by the total number of pixels within the quadrate. An average of the five quadrats was calculated to estimate the percent weed coverage in each plot.

2.2.2.3. Soil moisture and soil-surface residue

Three soil samples of 5 cm in diameter and 5 cm in depth were taken around each pitfall trap with a soil corer five times during the season of 2004 (10 and 26 May, 21 June, 6 July and 16 August) and four times in the season of 2005 (11 May, 15 and 28 July and 2 September). The three samples adjacent to each trap were homogenized and approximately 60 g of soil of each sample was used in a moisture analysis. The samples were weighed before and after drying for 48 h period at +105° C. Percent moisture was expressed on a wet basis. In an attempt to quantify the amount of soil-surface residue left from the previous crop, three soil corers (5 cm in diameter) were taken around each pitfall trap and dried under low light for 3 days. The straw and residue were sieved out from the soil by using a combination of mesh and hand picking and subsequently weighted on 11 May 2005.

2.2.3. Analysis

Species that could not be distinguished morphologically were pooled for analysis so that all specimens were retained. The group *Amara carinata* (LeConte, 1848) also included *Amara lacustris* LeConte, 1855 and *Amara torrida* (Panzer, 1797), and the group *Harpalus funerarius* LeConte, 1852 also included *Harpalus fraternus* Mannerheim, 1853. The catch for the entire growing season was analysed in 2004 but in 2005 only data from the period between 18 April and 25 May was used in the analyses due to a combination of weather and agronomy problems. Before analysing species composition and activity density, the two trap catches for each species on every sampling date in each plot were pooled and standardized by dividing the sum by the total number of trap days:

$$\text{Plot X} = \frac{\text{Carabids A} + \text{Carabids B}}{\text{Days A} + \text{Days B}}$$

where A and B are traps within the same experimental plot. This procedure allowed standardizing the catch for the occasional non-operational traps. Furthermore, the catch rates for all sampling dates were pooled for each plot to obtain a total catch rate for the year.

2.2.4. Diversity

Individual-based rarefaction analysis was applied to the data before standardization using the Vegan package (Jari et al. 2005) for rarefaction available in the R package (R Development Core Team 2005). Rarefaction curves were obtained from 1000 permutations of each sub-sample. Rarefaction has the advantage of standardizing for trapping effort as an explicit part of the procedure (Gotelli and Colwell 2001). Using rarefaction, I compared the estimated number of species at 1500 individuals in 2004 and at 600 individuals in 2005 due to differences in sample sizes. The average species richness, Shannon-Wiener and Evenness diversity indices were calculated using non-standardized catch rate.

Shannon-Wiener: $H' = -\Sigma$ ((proportion) x ln(proportion))

Evenness: ($J' = H'$/ln(species richness))

An ANOVA using corn varieties and agricultural regime as factors was then performed for these indices and planned comparisons (LSD test) were done to detect these statistically significant differences.

2.2.5. Species composition

A non-metric multidimensional scaling (NMDS) analysis was done to compare the species composition of beetle assemblages characterizing each treatment. In an NMDS ordination plot, distance between data points is directly proportional to species compositional dissimilarity (McCune and Grace 2002). For the 2005 data, NMDS was performed using log transformed total catch rate to avoid computational problem referred as *local minima* (McCune and Grace 2002). Sorensen (Bray-Curtis) distances were used to measure the dissimilarity matrix between samples. The starting coordinates were randomly selected. Forty runs with a maximum of 400 iterations were done using real data. This process was initially conducted with six dimensions, and then by reducing one dimension in each subsequent cycle. For each dimension, the best configuration was chosen based on stress value. In NMDS, the stress is a measure of distortion between the positions of real data points from the graphically presented data. Thus, low stress represents few distortions from the real position of the data points and is associated with a graphic that more accurately represents the dissimilarities in species composition. A preferred number of dimensions is suggested when adding an axis does not reduce stress by more than five. A Monte Carlo probability was then calculated to evaluate if the final stress is lower than 95% of 50 runs of randomized data.

The similarity in species composition among the four crop treatments was tested using multi-response permutation procedures (MRPP). MRPP is the non-parametric equivalent of MANOVA and uses Sorensen (Bray-Curtis) distances to calculate the variation within (A value) and between groups (T value) and evaluates the probability of these groups to be similar (McCune and Grace 2002). Homogeneity within a group increases when A approaches 1.0 while the between groups separation is greater when T is more negative. In addition, species vectors were calculated using a minimum r^2 of 0.3 and overlaid on the final ordination. The length and angle of each vector denote the strength of direction of the species association.

2.2.6. Indicator Species Analysis

Indicator species analysis (ISA) was performed using PcOrd (McCune and Mefford 1999) to identify associations between carabid species and treatment, regime or crop variety (Dufrêne and Legendre 1997). ISA evaluates the relative frequency and relative catch of a single species and compares these among the predefined treatments. The result is then compared with a randomly achieved value using a Monte-Carlo probability test. An indicator measure ranging between 0 (poor indicator) to 100 (good indicator) is then calculated with an associated P value from the Monte-Carlo test.

2.2.7. Activity Density

Carabid catch rates were $\log_{10}(x+1)$ transformed prior to the statistical analysis. The assumptions of normal distribution and equal variance for parametric analyses were achieved for the total carabid catches in 2004 and 2005 and for most carabid species after data transformations. To investigate the effect of the treatment on activity density of the total carabid catch, an ANOVA with corn variety (GMHT and conventional) and agricultural regime (continuous and rotation) and their interaction as factors was performed for the total carabid catch rate for the entire year. Block was used as a fixed factor to remove variability that may be attributed to site. Also, log transformed weed density was used as a covariate. The analysis was also repeated for each sampling date with repeated measures without the covariate. In 2004, the catch rates of the 10 most abundant species, which comprised more than 90% of the total catch, were used in a MANOVA comprising the same factor mentioned above to investigate the impact of corn variety and regime on the dominant species. In 2005, only the activity density of the five most abundant species was used in the MANOVA due to the small sample sizes of the rest of the species. In the case of significant MANOVA (Wilk's lambda $P < 0.05$), the effect of treatment on the activity density of single species was investigated using planned comparison (LSD *post hoc*) test.

2.2.8. Weed density and carabid activity density

Weed density data from vegetation surveys were not respecting the assumption of normality and equal variance required to perform parametric test after transformation in 2004 or in 2005; hence a non-parametric Kruskal-Wallis test was used to test the similarity of treatments in weed abundance for each sampling date. Only one date (May) was analysed in 2005 prior to the flooding event. The relationship between carabid catch and weed percent coverage was analysed after 25 May 2005. In 2004 only, the weed density data were categorized for each experimental plot within categories of low (< 45 weeds m^{-2}), medium (46 - 70 weeds m^{-2}) and high (> 71 weeds m^{-2}) weed density. Density was calculated by dividing the total number of weed from the three surveys by the surface area covered. A MANOVA using the ten most abundant carabid species was performed to investigate the response of the dominant species to the relative weed density. Planned comparisons (LSD) were applied to species responding significantly. A linear regression was performed using the $\log_{10}(x + 1)$ transformed activity density of carabids grouped by body size (small = $\leq$ 5 mm, medium = 6 – 9 mm and large = $\geq$ 10 mm) and the $\log_{10}(x + 1)$ transformed weed density. This allowed me to investigate the hypothesis that carabids respond differently to weed abundance depending on their body size. In 2005, the percent cover of weeds was used to perform a regression analysis on the catch rate of the carabids grouped by body size. Sampling dates near the weed coverage survey (22 July, 3 and 25 August) were pooled prior to analysis. Since three categories of body size (small, medium and large) were tested at the same time, a Bonferroni correction was applied ($P/n_{\text{comparison}}$) for multiple comparisons.

2.2.9. Soil moisture and soil-surface residue

In 2004, an ANOVA with repeated measures, using corn variety, agricultural regime and their interaction as model factors, was performed with percent soil moisture measured around each pitfall trap (2 per plot) from each sampling date as dependent variables. In 2005, only data from the sample taken on 11 May were used in the same ANOVA model without repeated measures since it was the only date where soil moisture was measured before the flood. The soil-surface residue from the six soil corer samples, taken in each plot, were pooled to form one sample per plot. Because the hypothesis was that rotation would increase the amount of soil-surface residue, a student's *T*-test was performed to compare plots under rotation to plots under continuous regime.

All statistical analyses were performed using SPSS 11.0 (SPSS Inc. 1999), except NMDS and MRPP tests using PcOrd (McCune and Mefford 1999).

2.3. Results

2.3.1. Carabid fauna

Between 3 May and 25 August 2004, I collected a total of 8006 carabid beetles representing 48 species in 15 genera (Appendix 1). The most abundant species was *Bembidion quadrimaculatum* L., 1761, which represented approximately 28% of the total carabid catch. The peak activity of this beetle occurred during the last two weeks of June. Other species commonly trapped in mid-summer were *Bembidion timidum* (LeConte, 1848), *Microlestes linearis* (LeConte, 1851) and *Poecilus scitulus* LeConte, 1848. The carabids most frequently captured in spring were *Poecilus corvus* (LeConte, 1873) and *Amara farcta* LeConte, 1855, while species peaking in late summer were dominated by *Pterostichus melanarius* (Illiger, 1798) and *Amara carinata* (LeConte, 1848). The 10 most abundant species represented 90.3 % of the total catch. Twenty-two species were caught 10 times or less, with 11 of these caught only once.

In 2005, a total of 3907 carabids from 34 species in 12 genera were caught between 15 April and 24 May (Appendix 1). *Amara farcta* was the most abundant species, representing 69.4 % of the total catch. The five most abundant species represented 91.7 % of the carabid catch. Eighteen species were caught 10 times or less, of which nine species were caught only once.

2.3.2. Diversity

In both years, rarefaction curves indicated lower carabid diversity in corn grown under rotation than in continuously cropped corn (Figure 2). In addition, when carabid diversity was compared between crop varieties within each agricultural regime, the type of herbicide applied had little discernable impact on carabid diversity. In 2004, the rarefaction curves suggested that the GMHT crop harbored slightly higher diversity than the conventional crop when compared with their respective rotation regimes. However, the opposite tendency was observed in 2005 when only data about species active in the spring were collected. Estimates based on 1500 individuals in 2004 support the following ranking of treatments with respect to carabid diversity: GMHT continuous (36.1 species), conventional continuous (34.3), GMHT rotation (30.9) and conventional rotation (28.7). Estimates based on 600 individuals in 2005 support the following rankings: conventional continuous (21.8 species), GMHT continuous (21.5), conventional rotation (16.2), and GMHT rotation (15.2).

Diversity parameters followed the same pattern observed for the rarefaction. The average number of species differed among treatments in 2004 ($F_{3,12} = 5.521$, $P = 0.013$) where GMHT and conventional corn under continuous regime had the highest average numbers of species and conventional under rotation had the lowest (Table 2). In 2005, both rotation regimes presented a significantly lower evenness ($F_{3,12} = 38.420$, $P < 0.01$) and Shannon-Wiener diversity ($F_{3,12} = 39.892$, $P < 0.01$), even if their species richness was comparable to the other treatments and if they were on average not significantly different (Table 2).

2.3.3. Species composition

In the NMDS for both years, the plots under rotation, regardless of corn variety, were well separated from the continuous plots along both axes (Figure 3). Corn variety had the most influence in 2004 when the best fit NMDS ordination was a 2-dimensional plot that explained 92.7 % of the total variation (stress = 9.516, Monte Carlo $P = 0.0196$). The r^2 values for axes 1 and 2 were 0.662 and 0.295, respectively. Treatments had an overall significant effect on carabid species composition (MRPP, $T = -4.24$, $A = 0.20$, $P < 0.05$) and pair-wise comparisons using MRPP showed that only the conventional rotation and conventional continuous had similar species composition (MRPP, $T = -1.83$, $A = 0.11$, $P > 0.05$), while all other comparisons between treatments had distinct species compositions. Only one plot from the conventional rotation was not well grouped with the rest of the rotation (Figure 3). Vectors representing *Pterostichus melanarius*, *Amara littoralis* and *Poecilus corvus* pointed toward the conventional rotation while the vectors for abundance of *Bembidion quadrimaculatum*, *Bembidion timidum*, *Microlestes linearis* and *Bembidion obscurellum* pointed in the direction of conventional continuous cropping. No vectors for increasing beetle species abundance pointed toward the direction of GMHT under either continuous or rotation regime.

In 2005, the best fit NMDS ordination was a 2-dimensional plot with a stress of 2.442 (Monte-Carlo randomization test, $P = 0.0196$) that explained 96.1% of the variation in the data (Figure 3). The coefficient of determination (r^2) of the axes 1 and 2 were 0.898 and 0.063, respectively. There was an overall significant treatment effect on species composition (MRPP, $T = -5.20$, $A = 0.35$, $P < 0.05$). The pair-wise comparisons between treatments, using MRPP, revealed that only the plots with GMHT and conventional corn variety under rotation were associated with similar species composition (MRPP, $T = 0.94$, $A = -0.62$, $P > 0.05$). All the other comparisons between treatments suggested different species compositions. The vectors of *Amara farcta*, *Amara littoralis* and *Poecilus corvus* were strongly associated with the rotation regime, while the vectors of six other species pointed to the opposite direction, toward continuous regime. Three vectors: *Bembidion obscurellum*, *Bembidion rupicola* and *Bembidion quadrimaculatum*, pointed toward the continuous conventional crop, while the other three that pointed toward the GHMT continuous were *Harpalus amputatus, Agonum placidum* and *Amara carinata.*

2.3.4. Indicator Species Analysis

Indicator analysis performed for the data of 2004 and 2005 showed that several species were indicators of different treatments, regimes and corn varieties (Table 3). However, no species were indicators of the same agronomic practice for both years: for example, *Agonum placidum* (Say, 1823), the strongest indicator of rotation regime in 2004, became a strong indicator of continuous regime in 2005, and *Harpalus amputatus* Say, 1830., the only significant indicator species of treatment in 2004, changed from being an indicator of GHMT rotation to GHMT continuous in 2005. Likewise, *Bembidion quadrimaculatum* L. 1769., an indicator of the conventional corn variety in 2004, became an indicator of conventional continuous treatment in 2005, but both shared the same corn variety. The other strong indicators in 2004 were *Amara apricaria*, an indicator of conventional corn variety, and *Bembidion obscurellum*, an indicator of continuous regime. The strongest indicator species in 2005, *Amara littoralis*, was an indicator of the rotation regime. There were also year-to-year differences in the numbers of indicators: for example, seven species were indicators of continuous regime in 2005, compared with only one for the same regime in 2004. Only one species, *Poecilus corvus* was indicator of the GMHT corn variety, and that, only for one year.

2.3.5. Activity Density

2.3.5.1. Total catch rate

The four blocks and weed covariate had no effects in either year and, therefore, these terms were removed from the final model. In 2004, only corn variety significantly affected the carabid catch rate ($F_{1,12} = 7.895$, $P = 0.016$) (Table 4). More carabids were captured in the conventional than in the GMHT corn variety. However, neither cultural regime nor the interaction term significantly affected the total carabid catch. In 2005, regime had a significant effect on the total carabid catch rate ($F_{1,12} = 26.033$, $P < 0.001$): more carabids were captured under rotation than under continuous cultivation. Using repeated measures with the carabid activity density on each sampling date, date interacted with both corn variety ($F_{8,96} = 2.267$, P = 0.029) and cultural regime ($F_{8,96} = 5.941$, P < 0.001). Additionally, the carabid activity density was significantly affected by corn variety in 14 June, and 1 and 14 July, while the agricultural regime had a significant effect in 17 May, and 11 and 25 August (Table 5). Plots with GMHT corn variety or continuous regime were associated with lower carabid catches than were other plots. In terms of the influence of corn variety and agricultural regime on the activity density of the most abundant carabids over time, *Bembidion quadrimaculatum* had the lowest activity density in rotation at the beginning of the season and in the GMHT crop in the middle of the summer (Figure 4). *Pterostichus melanarius* had a peak activity density in the rotation at the end of the season (Figure 4). Overall, these results suggest that effects of both crop variety and agricultural system on beetles can be somewhat stage specific, depending on phenology of the beetles and introducing a fair amount of complexity into the interpretation of assemblage patterns.

2.3.5.2. Activity density of single species

There was no effect of corn variety or agricultural regime on the activity density of the 10 most abundant carabids in 2004 (Table 4). In 2005, when analysis was restricted to the early season, the five most abundant species were significantly affected by cultural regime ($F_{5,8} = 15.177$, $P = 0.001$). *Amara farcta* ($F_{1,12} = 41.028$, $P < 0.001$) and *Amara littoralis* ($F_{1,12} = 41.028$, $P < 0.001$) were more abundant in the rotation regime.

2.3.5.3. Weed density and carabid activity density

Weed abundance was significantly associated with particular treatments at each sample date in 2004 (Kruskall-Wallis test; May: $T_{3,\,0.05} = 8.164$, $P = 0.043$; June: $T_{3,\,0.05} = 12.791$, $P = 0.002$; July: $T_{3,\,0.05} = 10.354$, $P = 0.016$) (Figure 5). Weed density in both conventional corn varieties (continuous and rotation) decreased from May to June and July. Weed abundance in GMHT corn varieties (continuous and rotation) was low in May, increased in June and decreased in July. Average weed abundance was lowest in conventional continuous treatments in June and July. The high weed abundance in plots of conventional rotation in May was due principally to kochia (*Kochia scoparia* L.). High average weed abundance in GMHT (both continuous and rotation) in June was almost exclusively due to redroot pigweed (*Armaranthus retroflexus* L.). In 2005, treatment had no significant effect on average weed abundance, although a slight trend was showing a higher weed density in GMHT under continuous regime.

There was no significant effect of weed cover on catches of the most abundant carabid species (10 in 2004 and 5 in 2005). In 2004, however, and despite the lack of significant MANOVA results, three species appeared to respond to weed categories: *Microlestes linearis*, *Bembidion quadrimaculatum* and *Bembidion timidum* were all captured more frequently in plots where weed density was low (Figure 6). The correlation of carabid body size and weed abundance in 2004 was non-significant after Bonferroni correction (0.05 / 3), but small-bodied carabids tended to be negatively affected by an increase in weed density ($P = 0.034$; Figure 7). In 2005, large-bodied carabids responded significantly to weed cover ($P = 0.013$, $R^2 = 0.368$) while the small and medium size showed no preference ($P = 0.640$, $R^2 = 0.016$ and $P = 0.532$, $r^2 = 0.169$ respectively). As weed coverage increased, more large-bodied carabids were captured (Figure 8). Since *Pterostichus melanarius* was the dominant large carabid and concerns that this species determined the result of the analysis, the regression analysis was repeated subtracting the activity density of *Pterostichus melanarius* from the total activity density of the large-bodied carabid. Without *Pterostichus melanarius*, the large carabids showed significantly the same pattern observed with a better explanation of the variance ($P = 0.005$, $r^2 = 0.445$).

2.3.6. *Soil moisture and soil surface residue*

In 2004, soil moisture was significantly higher in plots cropped under rotation than in those from the continuous cropping regime ($F_{1,28} = 27.330$, $P < 0.001$). In 3 of 5 sampling dates (10 May, 21 July and 16 August), plots under rotation had significantly higher soil moisture than those from the continuous system (Figure 9). This result also held for 2005 (10.4 ± 0.6 % under rotation compared to 8.5 ± 0.4 % in the continuous cropped blocks; $F_{1,28} = 7.296$, $P = 0.012$). The plots under rotation also had a significantly higher amount of soil-surface residue than plots under continuous regime ($T_{14, 0.05} = 3.438$, $P = 0.004$) with an average of 682.1 ± 81.0 mg compared to 356.6 ± 49.1 mg.

2.4. Discussion

2.4.1. Effects of Corn Varieties

A lower carabid activity density in GMHT corn was observed in 2004 but not in 2005. This may be due to the analysis of the 2005 data being restricted only to the period prior to environmental and agronomic problems. In 2004, we observed a strong emergence of redroot pigweeds (Amaranthus retroflexus L.) in the mid-season almost exclusively in the GMHT plots, which considerably increased the weed density. This late-emerging weed was not controlled by the first pre-burn spray of Roundup® (glyphosate) in GMHT plots, as it was probably present in the seedbank at that time; Roundup® has a low soil residual activity and does not kill seeds. Higher weed biomass in GMHT corn compared to conventional corn was also reported by Hawes et al. (2003). This considerably modified the micro-environment of the GMHT plots. Generally, loss of weed cover increases soil temperature and decreases soil moisture (Brust 1990); both of those variables that can affect differently the activity density of carabids depending on species.

Bembidion quadrimaculatum, had consistently lower activity density in GMHT than conventional corn plots. This species is known to prefer warmer, drier and weed-free environment (Rivard 1964, Kromp 1990). *Bembidion quadrimaculatum* and two other species of similar biologies, *Bembidion timidum* and *Microlestes linearis*, were less abundant in the GMHT crop due to its high weed density. A similar situation was described by Floate et al. (1990) where high density of chickweed (*Stellaria media* (L.)) reduced the activity density of *Bembidion* *quadrimaculatum*. Since these three species combined represented one third of the assemblage, the observed activity density of the entire assemblage was lower in the GMHT corn plots. Brooks et al. (2003) also reported *Bembidion* species to be more abundant in conventional than GMHT corn. Additionally, corn variety affected the carabid activity density only in the trapping period between June 14 to July 14 (see table Table 5), which corresponded to the peak activity density of *Bembidion quadrimaculatum*, *Bembidion timidum* and *Microlestes linearis* and the strong emergence of redroot pigweed. Although many studies have reported no effect of GMHT corn on the entire carabid assemblage (Brooks et al. 2003, Hawes et al. 2003), these results agree with studies reporting some variations in the response of some species (Brooks et al. 2003, Roy et al. 2003). In fact these results are contradictory to Haungthon et al. (2003) who reported higher carabid density in GMHT corn. In our study, no other dominant species responded to corn variety. This may be a consequence of the similar micro-environment between corn varieties after control of redroot pigweed in the mid-season.

Contrary to my initial hypothesis, corn variety had no effect on carabid diversity either year. This may partly be explained by the fact that most species, excluding those mentioned above, did not respond differently to corn varieties. Also, species richness between corn varieties was equivalent. From these results, there is no evidence that GMHT corn would have a lower carabid diversity than conventional corn. In fact, it may support the statements made by Dewar et al. (2003) concerning the creative use of GMHT to promote weeds and insects without compromising the yield.

2.4.2. *Effect of cultural regime*

Contrary to my initial hypothesis, in both years, carabid diversity and richness were the lowest when corn was rotated with canola. In 2005, when the samples were restricted to the early season, the number of species between continuous and rotation cropping were equivalent. However, the high abundance of *Amara farcta* in the rotation plots lowered the evenness index which consequently lowered the diversity measure of the rotation treatments. This is contrary to Lövei (1984) who reported that corn grown in rotation had higher species richness than continuous corn. However, corn in his study was rotated with wheat instead of canola. The low species richness in the rotation regime of the present study may be a consequence of the higher abundance of soil-surface residue left from the canola harvesting, which could have acted to obstruct movement and diminish pitfall catches, at least for some carabid species. In fact, many small-bodied carabids, such as *Bembidion* species, were less abundant in rotation treatments. This is similar to Humphreys and Mowat (1994) who found fewer carabids in treatments with (organic) straw input after the first. They also suggested that the straw may have obstructed the carabid movements. An increase in vegetative debris impeding carabid movement was also reported by Greenslade (1964). Additionally, the constant higher soil moisture in the rotation may also have discouraged species that prefer a dry environment such as *Bembidion quadrimaculatum*.

Rotating corn with canola had a much stronger influence in shaping the carabid community structure in both years than did the possible effect of corn variety. Additionally, in both years, the mean carabid activity density was higher in corn under rotation, a result also reported by Brust et al. (1986). In a study conducted in Lethbridge and Lacombe, Alberta, Butts et al. (2003) found that canola provides a good habitat for many carabids, especially for the *Amara* species. The dominance of *Amara farcta* in 2005 is probably a reflection of the rotation effect, which increased canola residues at the soil surface, and may also have attracted the less abundant *Amara littoralis*. *Amara* species are known to eat seeds of crucifer plants such as canola (Thiele 1977). Therefore, I hypothesis that plenty of canola residue such as pods or seed were left on the ground after harvest which attracted the *Amaras*. It is interesting to note that in 2004, the opposite trend was observed for *Amara farcta* and cultural regime, but at that time, its abundance was much lower. This probably explains why in 2004, even if the mean carabid activity density was higher under rotation, no significant effect of cultural regime on the total carabid activity density was found. On the other hand, activity density of some species seemed to have been enhanced by the rotation. Mean activity density of *Pterostichus melanarius* and *Poecilus corvus* were both higher under rotation. This trend may have been a reflection of the potentially higher prey availability in rotation treatments. In fact, the higher amount of residue left on the ground may have contributed to increase the organic matter, a variable often associated with increased micro-arthropod abundance.

2.4.3. Carabid body size and weed abundance

Intuitively, large-bodied carabids should be more constrained in their movements under dense vegetation than small-bodied carabids. Therefore, trapping carabids in dense vegetation should give a more accurate estimation of the activity density of the small-bodied carabids than the large-bodied carabids. It is therefore expected that the mis-representation of carabids captured under a dense vegetation habitat would be greater for the larger carabids. However, in 2005, more large-bodied carabids were captured as weed density increased. In 2004, fewer small-bodied carabids were captured under dense vegetation. Although two different weed survey methods and trapping periods were used between years due to the unexpected weather problems, I argue that those data are a good reflection of carabid habitat preferences. For instance, Brust (1990) also reported that mainly the larger carabids were leaving areas controlled by herbicide, suggesting that weed density is an important component of their habitat. In contrast, Brust (1990) also showed that alteration of foliage did not seem to disturb the smaller carabids.

Habitat preference for large or small-bodied carabids could be a reflection of their feeding-guild. Prey items of large-bodied carabids are generally larger than small-bodied carabids. Dense weed stands will generally attract a greater diversity of prey. Additionally, larger carabids are more prone to be predated on by birds than smaller ones and weeds may offer good coverage. Also, many small carabids species from the genus *Bembidion* represented in this study are primarily diurnal hunters that require visual cues to find insect eggs or larvae and a high weed-density may reduce their ability to prey. Chiverton (1988) reported that searching of prey increase with temperature, a variable that usually is reduced under high weed coverage. Another explanation could be the predominantly nocturnal activity of the larger carabids (i.e *Pterostichus*) and the diurnal activity of the smaller species (i.e. *Bembidion* spp.).

Baker and Dunning (1975) suggested that nocturnal carabids have a larger activity period under ground cover while the opposite was suggested for diurnal species.

2.5. Conclusions

The present study suggests that cropping system affects carabid diversity, species composition and activity density more significantly than the type of herbicide used. Rotation of corn with canola increased the amount of mulch on the soil surface and this maintained soil moisture well. This aspect probably affected species in different ways: for example, large carabids may have found more food items among the mulch, whereas small carabids may have been physically restricted in their ability to move within and colonize these plots because of their fine-grained resistance to overland movement that larger species may simply walk over. The use of Roundup® or conventional herbicide also affected the carabids indirectly through their efficacy in controlling weeds (Figure 5). The abundance of weeds affected the activity density of the small and the large-bodied carabid species. Therefore, with regard to pest management strategies, tolerating a moderate amount of weeds within a corn field without compromising yield may help reduce pest density. Also, using canola in rotation with corn seems to be a good pest management strategy as it augmented carabid abundance, especially the seed feeders in 2005 which can potentially contribute in the reduction of weed populations. Although rotation decreased diversity, it did not reduce the species richness. With regard to GMHT corn, no severe negative effects were noticed on the carabid community over this short-term study except maybe for *Bembidion quadrimaculatum* that apparently responded negatively to the lack of control of redroot pigweed in mid summer. Therefore, GMHT corn could be used in the same fashion as the conventional corn with respect to carabid population and pest management strategies.

List of Tables

Table 1: The treatments and their agronomic characteristics in 2004 and in 2005.

					Treatment Application Date	
Corn variety	Regime	Herbicide	Active ingrediant	Rate (g ai/ha)	2004	2005
1 - Roundup Ready (GMHT)	Continuous	Roundup WeatherMax	Glyphosate	890	20.V, 16.VI, 29.VI	27.V, 12.VII
		Pardner	Bromoxynil	345	—	24. VI
		Poast Ultra	Sethoxydim	333	—	24. VI
2 - Roundup Ready (GMHT)	Rotation*	Roundup WeatherMax	Glyphosate	890	20.V, 16.VI, 29.VI	27.V, 12.VII
		Pardner	Bromoxynil	335	—	27.V, 24.VI,12.VII
		Poast Ultra	Sethoxydim	333	—	24. VI
3 - Conventional	Continuous	Atrazine	Atrazine	1186	20.VI	—
		Eradicane 8-E	EPTC	4349	—	26.V
		Buctril	Bromoxynil / MCPA	554	—	12.VII
		Pardner	Bromoxynil	345	—	24. VI
		Poast Ultra	Sethoxydim	333	—	24. VI
4 - Conventional	Rotation**	Eradicane 8-E	EPTC	4349	20.VI	26.V
		Buctril	Bromoxynil / MCPA	554	16.VI	12.VII
		Pardner	Bromoxynil	345	—	24. VI
		Poast Ultra	Sethoxydim	333	—	24. VI

* Roundup Ready canola grown previous year

** Conventional canola grown previous year

Table 2: Carabid abundance and diversity in each treatment. Letters represent groupings of similar values (LSD test, $P < 0.05$) after significant ANOVA ($P < 0.05$) within the same column. Non standardized catch are used for the average carabids

Treatment	Total number of carabids	Average carabid (n = 4)	Shannon-Wiener (H')	Evenness (J')	Species richness	Mean species richness (n = 4)
2004						
GMHT continuous	1640	410.0 ± 19.8	2.26 ± 0.05a	0.700 ± 0.020a	37	25.5 ± 1.3bc
Conv continuous	1972	493.0 ± 40.4	2.20 ± 0.05a	0.661 ± 0.010a	36	27.8 ± 0.8c
GMHT rotation	1786	446.5 ± 47.3	2.13 ± 0.06a	0.684 ± 0.010a	32	22.8 ± 1.0ab
Conv rotation	2608	652.0 ± 82.5	2.06 ± 0.11a	0.667 ± 0.022a	32	22.0 ± 1.4a
2005						
GMHT continuous	737	184.3 ± 24.3	1.60 ± 0.06a	0.58 ± 0.02a	24	15.8 ± 0.6a
Conv continuous	527	131.8 ± 14.9	1.76 ± 0.06a	0.64 ± 0.02a	22	15.3 ± 1.0a
GMHT rotation	1369	342.3 ± 62.4	0.89 ± 0.09b	0.35 ± 0.04b	22	13.0 ± 0.4a
Conv rotation	1274	318.5 ± 43.2	0.88 ± 0.08b	0.34 ± 0.02b	23	13.0 ± 1.5a

Table 3: Significant indicator species of the treatments, regimes and crop varieties in 2004 and 2005 (Monte-Carlo randomization, $P < 0.05$).

2004		
Species	Treatment	Indicator value
Harpalus amputatus	GHMT rotation	51.5
	Regime	
Pterostichus melanarius	Rotation	69.7
Poecilus corvus	Rotation	60.2
Bembidion obscurellum	Continuous	76.0
Agonum placidum	Rotation	79.3
	Variety	
Bembidion quadrimaculatum	Conventional	63.6
Amara apricaria	Conventional	77.9
Bembidion timidum	Conventional	66.6
2005		
Species	Treatment	Indicator value
Harpalus amputatus	GHMT continuous	55.2
Harpalus herbivagus	GHMT continuous	72.3
Harpalus funerarius	GHMT continuous	64.2
Bembidion quadrimaculatum	Conventional continuous	63.3
Clivina fossor	Conventional continuous	58.1
Agonum placidum	GHMT continuous	55.9
Microlestes linearis	Conventional continuous	77.1
Bembidion rupicola	Conventional continuous	60.7
	Regime	
Amara farcta	Rotation	76.6
Amara littoralis	Rotation	97.6
Clivina fossor	Continuous	84.6
Bembidion quadrimaculatum	Continuous	81.8
Harpalus amputatus	Continuous	77.8
Poecilus scitulus	Continuous	72.1
Agonum placidum	Continuous	71.5
Harpalus herbivagus	Continuous	75.1
Harpalus funerarius	Continuous	68.6
	Variety	
Poecilus corvus	GHMT	62.0

Table 4: Mean ± SE (n = 8) activity density (beetle / trap days) of carabid species in different corn varieties and cropping regimes for 2004 and 2005.

	Corn variety			Cultural regime		
2004	GMHT	Conventional	*P*	Continuous	Rotation	*P*
Total carabid catch	14.3 ± 0.78	18.9 ± 1.61	0.016	15.1 ± 0.85	18.1 ± 1.83	0.122
MANOVA	—	—	0.332	—	—	0.149
H. amputatus	0.37 ± 0.05	0.41 ± 0.07	0.684	0.45 ± 0.06	0.34 ± 0.05	0.223
A. carinata	0.87 ± 0.15	1.47 ± 0.37	0.142	1.01 ± 0.16	1.32 ± 0.39	0.575
P. corvus	1.51 ± 0.18	1.59 ± 0.18	0.728	1.23 ± 0.13	1.87 ± 0.14	0.015
A. farcta	0.83 ± 0.12	0.65 ± 0.10	0.257	0.90 ± 0.10	0.58 ± 0.10	0.049
M. linearis	0.40 ± 0.06	0.63 ± 0.10	0.105	0.58 ± 0.10	0.44 ± 0.08	0.303
P. melanarius	4.01 ± 0.54	3.83 ± 1.08	0.427	2.37 ± 0.39	5.46 ± 0.80	0.015
Ag. placidum	0.28 ± 0.06	0.68 ± 0.32	0.132	0.19 ± 0.05	0.76 ± 0.31	0.017
B. quadrimaculatum	3.35 ± 0.37	5.84 ± 0.77	0.015	5.12 ± 0.53	4.08 ± 0.89	0.122
P. sciutlus	0.60 ± 0.13	1.01 ± 0.18	0.128	0.77 ± 0.19	0.84 ± 0.16	0.7
B. timidum	0.51 ± 0.11	1.02 ± 0.15	0.040	0.87 ± 0.13	0.67 ± 0.18	0.283
2005						
Total carabid catch	12.2 ± 1.96	10.3 ± 1.89	0.194	7.32 ± 0.80	15.2 ± 1.86	<0.001
MANOVA	—	—	0.142	—	—	0.001
H. amputatus	0.48 ± 0.12	0.24 ± 0.06	0.010	0.56 ± 0.11	0.16 ± 0.09	<0.001
P. corvus	1.89 ± 0.19	1.16 ± 0.23	0.024	1.26 ± 0.29	1.79 ± 0.34	0.060
A. farcta	8.30 ± 1.95	7.11 ± 1.84	0.213	3.60 ± 0.53	11.8 ± 1.68	<0.001
A. littoralis	0.41 ± 0.18	0.40 ± 0.18	0.997	0.01 ± 0.01	0.80 ± 0.16	<0.001
B. quadrimaculatum	0.18 ± 0.03	0.52 ± 0.18	0.013	0.57 ± 0.17	0.12 ± 0.18	0.001

Table 5: Average activity density (beetle / trap days) ± SE (n = 8) of carabids in different corn variety and cropping regime for each sampling date in 2004.

	Corn varieties			Cultural regimes		
Date	GMHT	Conventional	*P*	Continuous	Rotation	*P*
17-May	2.01 ± 0.23	1.98 ± 0.24	0.903	2.46 ± 0.12	1.54 ± 0.19	0.003
14-Jun	1.36 ± 0.09	2.33 ± 0.37	0.007	2.14 ± 0.41	1.54 ± 0.13	0.103
01-Jul	2.21 ± 0.23	3.76 ± 0.66	0.048	2.85 ± 0.35	3.12 ± 0.74	0.952
14-Jul	2.40 ± 0.22	3.50 ± 0.31	0.018	2.98 ± 0.21	2.92 ± 0.43	0.642
28-Jul	1.28 ± 0.24	1.06 ± 0.26	0.438	0.88 ± 0.17	1.45 ± 0.28	0.153
11-Jul	1.37 ± 0.19	2.20 ± 0.47	0.206	1.22 ± 0.27	2.35 ± 0.38	0.025
25-Aug	1.72 ± 0.23	1.85 ± 0.48	0.756	1.11 ± 0.29	2.46 ± 0.26	0.004
13-Sep	1.29 ± 0.18	1.73 ± 0.64	0.680	0.88 ± 0.12	2.14 ± 0.57	0.016
30-Sep	0.62 ± 0.05	0.50 ± 0.08	0.219	0.55 ± 0.04	0.57 ± 0.09	0.972

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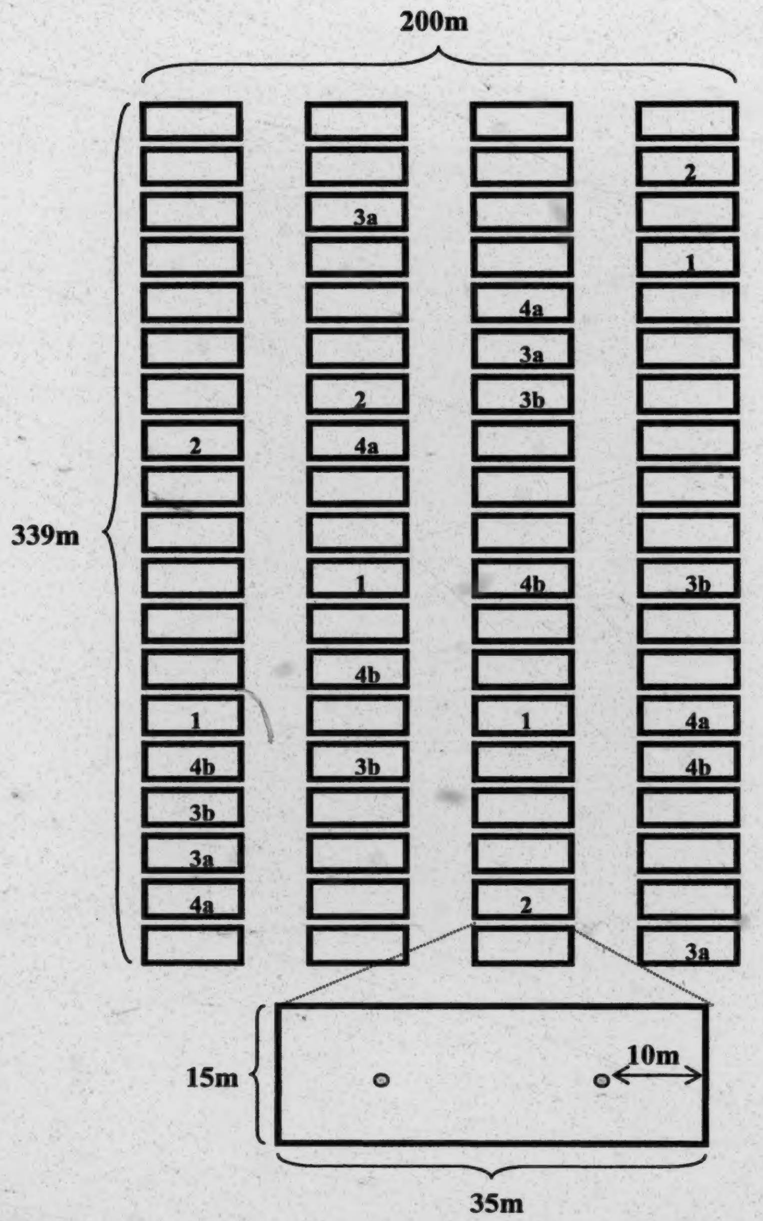
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Figure 1: Location of pitfall traps (circles) in each experimental plot within study site (not in scale). GMHT continuous (1) and Conventional continuous (2) were sampled in both years; GMHT rotation (3) Conventional rotation (4) were sampled in 2004 (a) and 2005 (b).

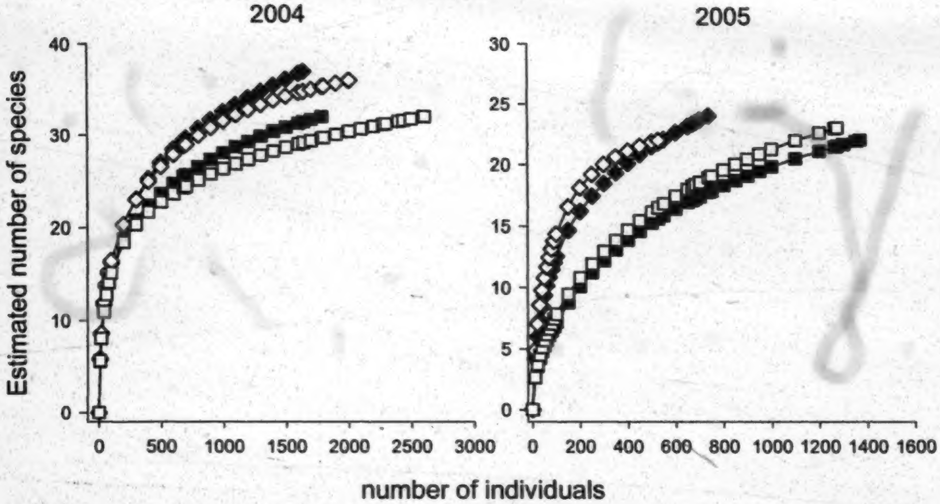

Figure 2: Rarefaction (species accumulation) curves for carabid diversity among weed management treatments in 2004 and in 2005. The curves show rotation regime (squares) and continuous regime (diamonds) for the corn variety GMHT (black) and conventional (white). Each curve ends at the maximum number of individuals caught in each of the four treatments.

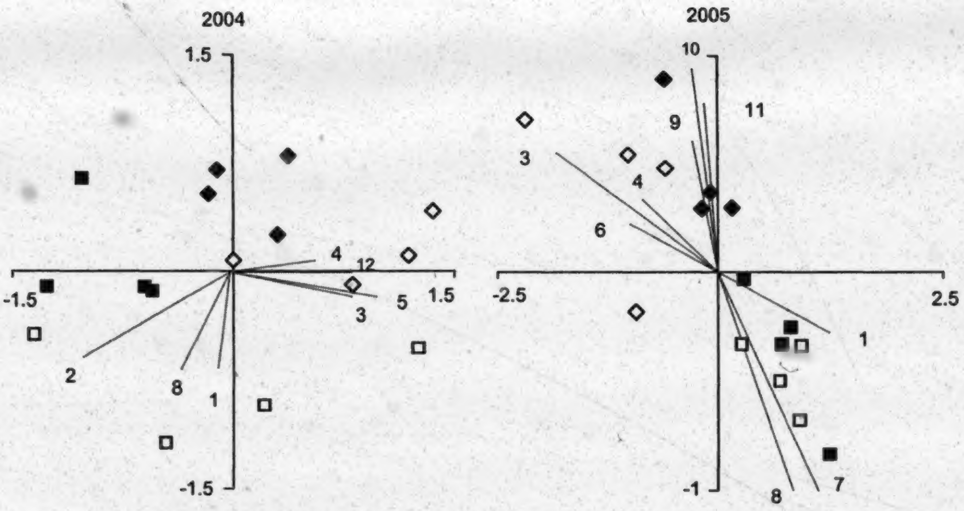

Figure 3: Non-metric multidimensional scaling (NMDS) ordination (Bray-Curtis distance measurement) using the entire carabid catch collected in 2004 or in 2005. Axis 1 is horizontal and axis 2 vertical. Cropping regimes are represented by squares (rotation) and diamonds (continuous), with corn varieties is shown in black (GMHT) and white (conventional). Species vectors (dash lines) with a minimum r^2 of 0.3 are: 1: *P. corvus*, 2: *P. melanarius*, 3: *B. quadrimaculatum*, 4: *B. timidum*, 5: *B. obscurellum*, 6: *B. rupicola* 7: *A. farcta*, 8: *A. littoralis*, 9: *A. carinata*, 10: *Ag. placidum*, 11: *H. amputatus* and 12: *M. linearis*.

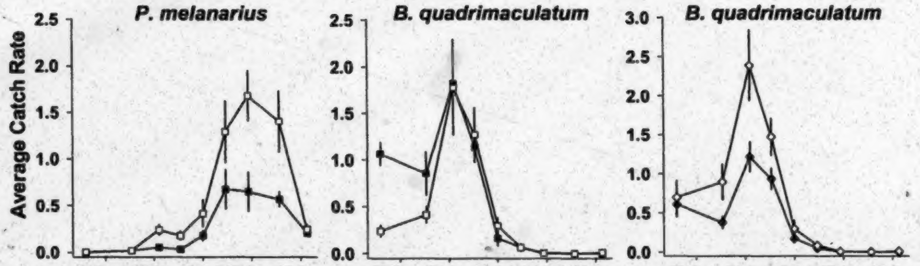

Figure 4: Seasonality of two carabid species in the studied treatments. Squares represent the cultural regime (black =continuous, white = rotation), and diamonds represent corn variety (black = GMHT, white = conventional). Each data point is an average of 8 plots ± SE.

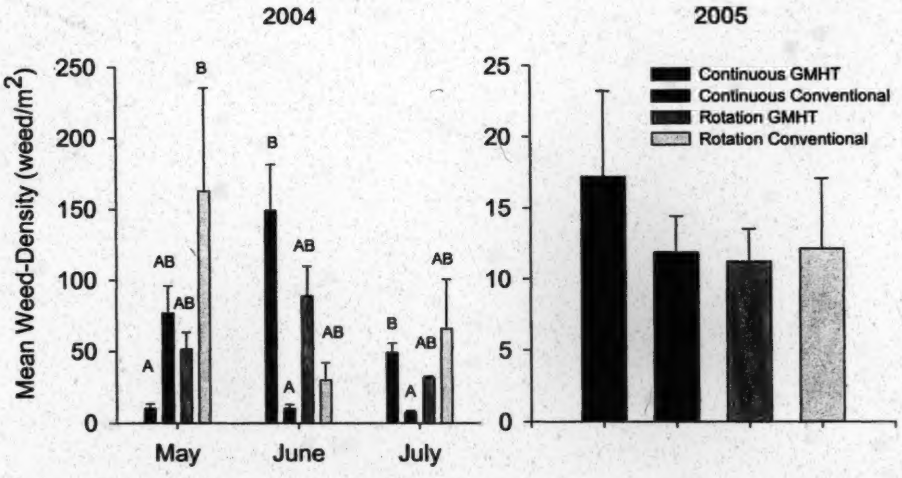

Figure 5: Average weed density ± SE (n=4 for each column) in the four treatments for three survey dates in 2004 and one survey (May) in 2005. Letters represent grouping within each survey date after significant Kruskall-Wallis test ($P < 0.05$).

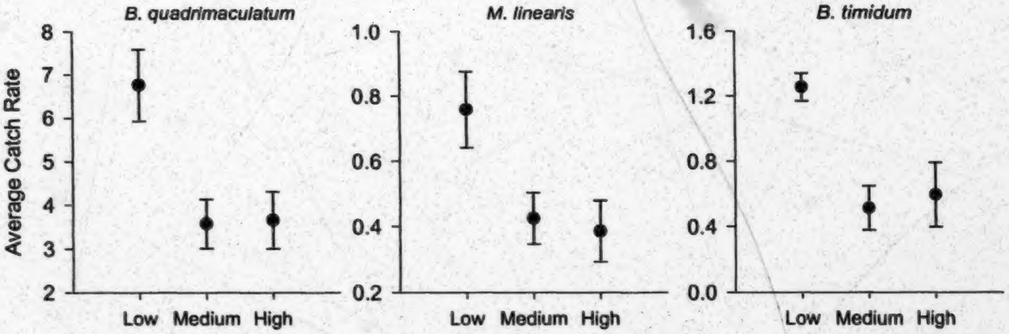

Figure 6: Average activity density ± SE (low n = 5, medium n = 5, and high n=6) of three carabid species in relation to the weed abundance in 2004. Weed categories were selected according to weed density (see text).

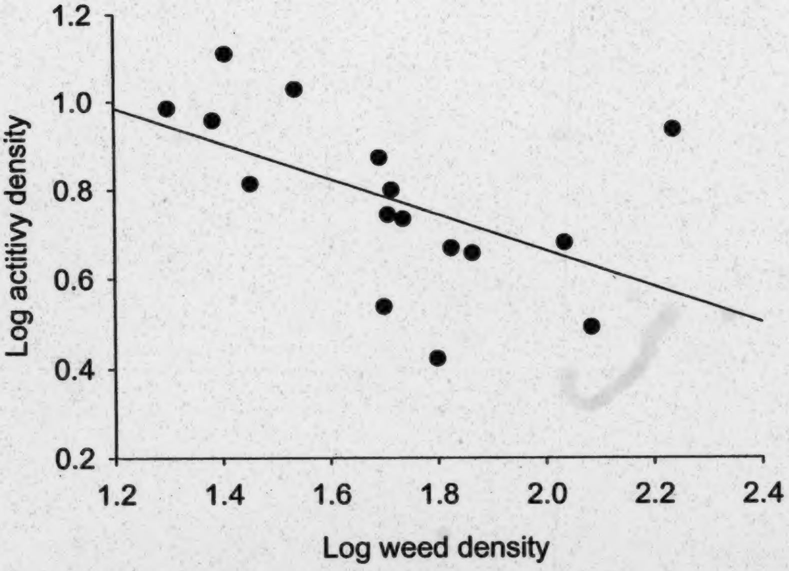

Figure 7: Activity density of small-bodied carabids (see text) with increasing weed density in 2004 ($r^2 = 0.284$, $P = 0.034$). Each data point corresponds to one experimental plot.

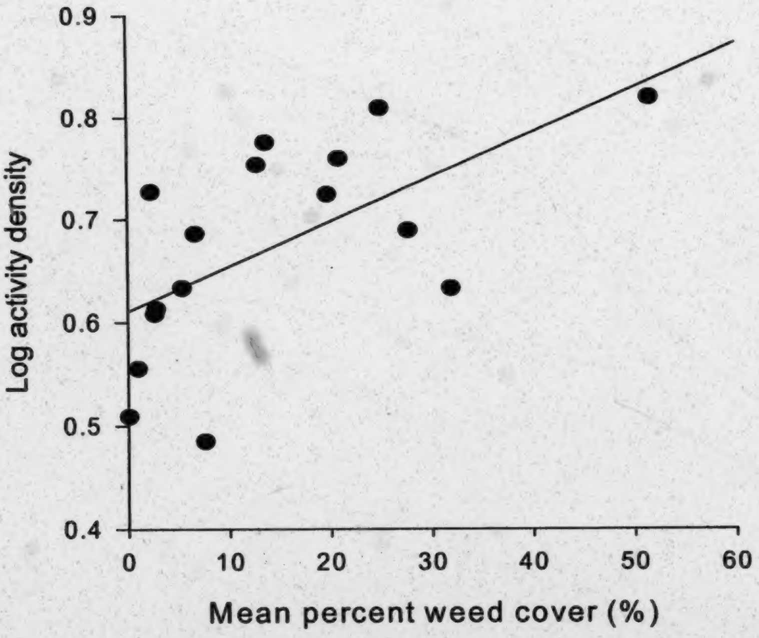

Figure 8: Activity density of large-bodied carabid species (see text) with increasing weed coverage in 2005 ($r^2 = 0.368$, $P = 0.013$). Each data point corresponds to one experimental plot.

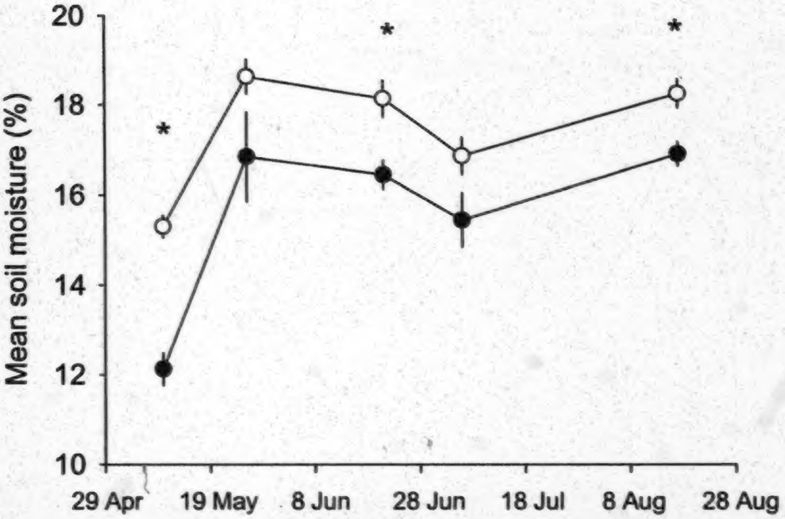

Figure 9: Average soil moisture ± SE (n = 8) in plots under rotation (open symbols) and continuous (black symbols) in 2004. The asterisks indicate dates when the soil moisture was significantly different between the two cropping regimes.

Appendices

Appendix 1: Carabid species caught in 2004 and in 2005 including catch frequency.

	2004		2005	
Species	Count	Proportion	Count	Proportion
Agonum corvus (LeConte, 1860)	6	<0.01	2	0.05
Agonum cupreum Dejean, 1831	2	<0.01	1	0.02
Agonum placidum (Say, 1823)	220	2.7	16	0.40
Amara apricaria (Paykull, 1790)	38	0.4	2	0.05
Amara carinata (LeConte, 1848)	593	7.4	9	0.23
Amara confusa LeConte, 1848	6	<0.01	2	0.74
Amara ellipsis (Casey, 1918)	1	<0.01	1	0.02
Amara erratica (Duftschmid, 1812)	2	<0.01	—	—
Amara farcta LeConte, 1855	342	4.2	2714	69.4
Amara latior (Kirby, 1837)	22	0.2	1	0.02
Amara littoralis Mannerheim, 1843	46	0.5	133	3.40
Amara obesa (Say, 1823)	11	0.1	—	—
Amara patruelis Dejean, 1831	1	<0.01	—	—
Amara quenseli (Schönherr, 1806)	178	(2.2	2	0.05
Amara torrida (Panzer, 1797)	3	<0.01	—	—
Axinopalpus biplagiatus (Dejean, 1825)	2	<0.01	—	—
Bembidion bimaculatum (Kirby, 1837)	3	<0.01	—	—
Bembidion nitidum (Kirby, 1837)	2	<0.01	1	0.02
Bembidion nudipenne Lindroth, 1963	25	0.3	1	0.02
Bembidion obscurellum (Motschulsky, 1845)	43	0.5	2	0.05
Bembidion quadrimaculatum (Linné 1769)	2239	27.9	132	3.37
Bembidion rapidum (LeConte, 1848)	1	<0.01	1	0.02
Bembidion rupicola (Kirby, 1837)	61	0.7	22	0.56
Bembidion timidum (LeConte, 1848)	345	4.3	2	0.05
Bradycellus congener (LeConte, 1848)	14	(0.1	5	0.12
Calosoma obsoletum Say, 1823	4	<0.01	—	—
Carabus granulatus Linné, 1758	3	<0.01	2	0.05
Chlaenius serriceus (Forster, 1771)	10	0.1	–	—
Clivina fossor (Linné, 1758)	130	1.6	50	1.27
Dicheirotrichus cognatus (Gyllenhal, 1827)	1	<0.01	—	—
Diplocheila obtusa (LeConte, 1848)	1	<0.01	—	—
Harpalus affinis (Schrank, 1781)	1	<0.01	—	—
Harpalus amputatus Say, 1830	189	(2.3	120	3.07
Harpalus fraternus LeConte, 1852	1	<0.01	1	0.02
Harpalus funerarius Mannerheim, 1853	69	0.8	25	0.63
Harpalus fuscipalpis Sturm, 1818	23	0.2	16	0.40
Harpalus herbivagus Say, 1823	26	0.3	35	0.89
Harpalus nigritarsis Sahlberg, 1827	1	<0.01	—	—
Harpalus paratus Casey, 1924	1	<0.01	—	—
Harpalus somnulentus Dejean, 1829	1	<0.01	—	—
Harpalus ventralis LeConte, 1848	2	<0.01	—	—

Microlestes linearis (LeConte, 1851)	246	3.0	13	0.33
Poecilus corvus (LeConte, 1873)	776	9.6	490	12.5
Poecilus lucublandus (Say, 1823)	22	0.2	20	0.51
Poecilus scitulus LeConte, 1848	373	4.6	20	0.51
Pterostichus adstrictus Eschscholtz, 1823	1	<0.01	1	0.02
Pterostichus melanarius (Illiger, 1798)	1905	23.7	23	0.58
Stenolophus comma (Fabricius, 1775)	14	0.1	14	0.35
Syntomus americanus (Dejean, 1831)	—	—	1	0.02
Total	8006		3907	

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3. Chapter 3 - Title

Carabid Assemblages in a Rotation of Three Different Crops in Southern Alberta, Canada: a Comparison of Sustainable and Conventional Farming

3.1. Introduction

Agricultural intensification, especially pesticide use and monoculture cultivation, has been shown repeatedly to negatively affect the structure of faunal and floral landscape. These effects include soil erosion and contamination, ground water pollution and biodiversity reduction (Edwards 1987, Pfiffner and Niggli 1996, Hole et al. 2005). In many if not most cases, these changes in soil, water and biodiversity have been linked to conventional farming systems with high chemical input and a predominant focus on high yield production. Not surprisingly, then, concerns about environmental and food quality have fueled increasing efforts to develop alternative farming practices. New concepts such as organic, low-input and sustainable farming have since emerged. Organic farming in its strictest sense excludes the application of any synthetic chemicals, such as pesticides and inorganic fertilizers. Sustainable or low-input farming practices integrate crop rotation, economic injury level, strip cropping, and other modern practices to minimize reliance on synthetic chemicals (Edwards 1987). One alternative method to reduce insecticide use is the conservation and, perhaps, enhancement of natural predators of pest arthropods. For example, carabid beetles (Coleoptera: Carabidae) can play an important role in reducing population sizes of potential insect pests (Menalled et al. 1999). The question is how can we maximize the extent and efficiency of this inexpensive, naturally provided pest management force?

Although effects of organic farming on carabid beetles have been well studied (Dritschilo and Wanner 1980, Armstrong 1995, Armstrong and McKinlay

1997, Bengtsson et al. 2005), impacts of sustainable farming have received less attention (Booij and Noorlander 1992, Fan et al. 1993, Pfiffner and Luka 2003). Carabids are an important component of the soil dwelling fauna because they prey on various agricultural pest insects (Frank 1971, Brust et al. 1985, Grafius and Warner 1989, Floate et al. 1990, Winder 1990). Several studies have reported increases in both diversity and activity density of carabids under organic farming (Dritschilo and Wanner 1980, Hokkanen and Holopainen 1986, Kromp 1989, Fan et al. 1993, Pfiffner and Niggli 1996), while others have reported no significant effects (Holopainen 1983, Armstrong 1995). Application of manure, a common organic fertilizer used in organic and sustainable farming, has been associated with increases in carabid activity density and diversity (Hance and Gregoire-Wibo 1987, Humphreys and Mowat 1994, Raworth et al. 2004). An observed increase in potential prey items (mainly springtails, Collembola) associated with manure application can explain this pattern (Hance and Gregoire-Wibo 1987). Moreover, manure application can be the single most important factor influencing farmland carabid community composition and can decrease the negative effects of the use of insecticides (Hance and Gregoire-Wibo 1987).

Low or no tillage are other sustainable agricultural practices, used to manage crop residue, incorporate organic matter into the soil and control weeds and arthropod pests (Musick 1987, Holland 2002). Tillage *per se* has severe effects on farmland soil fauna. For example, deep tillage reduces overall carabid abundance and diversity; however, some species may show a positive response (Thiele 1977, Kromp 1999, Holland and Luff 2000). Higher carabid diversity and abundance under systems with reduced or no tillage have been reported in many studies (House and Stinner 1983, House and Alzugaray 1989, Tonhasca 1993, Cárcamo 1995, Andersen 1999). However, some studies have found no significant effects of tillage on the overall carabid abundance (Cárcamo et al. 1995, Hummel et al. 2002). Responses of some carabid species have also been inconsistent between different tillage intensities (Ferguson and McPherson 1985, Brust et al. 1986, Cárcamo 1995), which may be consequences of carabid phenology and timing of tillage operations.

Considerable attention has been recently given to sustainable farming as a way to benefit farmers and consumers and to provide environmental benefits. Increasing the impact of beneficial arthropods on pest populations has the potential to reduce the need for pesticide use. Using agronomic practices to achieve this impact has the underlying assumption that sustainable farming actually is remarkably more beneficial for these insects than conventional farming. To evaluate this assumption, it is necessary to compare the impacts of these farming systems on carabid assemblages.

In this chapter, I investigate the responses of carabid beetles to three different crops under rotation (wheat (*Triticum aestivus* L.), potato (*Solanum tuberosum* L.) and bean (*Phaseolus vulgaris* L.)) and, two different levels of agricultural input: conventional and sustainable farming. I hypothesize that (1) sustainable agriculture increases overall carabid abundance and diversity by providing a more suitable habitat. The lack of tillage and the application of manure characteristic of sustainable treatments should benefit most species by reducing mortality and increasing food availability. (2) I expect crop type to influence carabid abundance and species composition by providing a different habitat structure. At maturity, beans and potatoes provide a strong canopy coverage, while wheat remains more open. Additionally, wheat has a higher plant density compared to beans or potatoes. Potato plots are expected to have a much lower carabid abundance since it is the only crop routinely treated with insecticide. In addition, I thought it was important to monitor the effects of these crops and farming methods on potential pests, and therefore, I examine the abundance of click beetles (Coleoptera: Elateridae). Wireworms, the larval stage of the click beetles, are pests of many crops including potatoes, corn, grain and root crops (Simmons et al. 1998). Larvae remain in the soil for several years causing crop damage by eating seed or tubers. It is expected that the lack of tillage in sustainable treatment increases their abundance.

3.2. Materials and Methods

3.2.1. Site Description and Agronomic Treatments:

This study was conducted near Vauxhall (50º03'19N - 112º07'51W), a region with brown chernozemic soil in the dry grassland of southern Alberta, Canada. It was part of a multidisciplinary research project with the aim to improve the sustainability of potato farming. The study site comprised 4 replicates of 26 plots (10.1 m x 18.3 m, inter-plot distances 2.0 m) separated by 18 m pathways (Figure 10). Inter-plots and pathways were seeded with fall rye (in 2000, 2003 and 2004) and winter wheat (in 2005) that was regularly mowed. Rotations, varying in length for 3 to 6 years, were established under conventional and sustainable management in 2000. Each phase of each rotation was present in each year. The present study used a subset of these plots and specifically included only a three-year rotation of wheat, potato and bean under sustainable and conventional treatments (Table 6). Carabid assemblages were sampled in all replicate plots in wheat, bean and potato plots of the three year rotation in both sustainable and conventional treatments for a total of 24 plots per year (in 2000 and 2003 to 2005).

The following practices differentiate the sustainable treatment from the conventional: (1) direct seeding or reduced tillage where possible, (2) fall-seeded cover crops in wheat and bean plots, (3) composted cattle manure as a substitute for inorganic fertilizer following potato crop, and (4) straight cutting of solid seeded rather than under-cutting of wide-row seeded bean plots. The latter practice may lead to soil erosion risk as it requires sub-soil disturbance to uproot the plants in contrast to standard harvesting of straight cutting in one operation with a combine, which leaves some stubble without disturbing the soil. Compost (derived from beef cattle feedlot manure) or inorganic fertilizers were applied in the preceding fall to potato plots but inorganic fertilizer was applied to the wheat and bean plots in the spring, in the 2004 season. In this year, the wet, early fall of 2003 prevented any application of compost or fertilizer until spring 2004. Fall cultivation involved one pass of a disc and harrow with the exception of the conventional potato treatment that was mouldboard ploughed. The sustainable bean and wheat plots were preceded by a fall-seeded cover crop of oats which was changed in 2004 to winter-hardy fall rye. Potato and wheat were seeded late April to early May, while bean plots were seeded later, in mid-May. In July 2005, two potato plots (one sustainable and one conventional) were terminated following flooding problems caused by extreme rainfall in June. Only potato plots were treated with insecticides, as is necessary for control of Colorado potato beetles (Leptinotarsa decemlineata (Say)) and aphids (Table 8)in this crop. Pesticide application rate and date are listed in (Table 7-9). All potato, wheat and sustainable bean plots had a desiccant (Reglone) applied before harvest. Irrigation was applied to all plots when needed throughout the season. Barley was grown over the whole experimental area in 1999 (the year prior to project initiation) to test for soil uniformity. Year 2000 was a base line year where crops were grown without application of treatment.

3.2.2. Sampling

3.2.2.1. Carabids

Carabids were collected in 2000 (pre-treatment year) and 2003-2005. The latter three years constituted the second cycle of the crop rotation; thus, compost had been used at least once on each selected rotation. Sampling periods were as follows: (1) 01 July to 25 Aug. 2000; (2) 12 June to 27 Aug. 2003; (3) 18 May to 01 Sept. 2004, and (4) 03 May to 29 Aug. 2005. Two pitfall traps were placed in opposite corners of each study plot, 2 meters from the plot edge, and 5 meters into the plot interior to sample carabids (Figure 10). Sampling was done using plastic pitfall traps: a 1-L plastic container was inserted in the ground flush with soil surface, and it contained a 0.5-L plastic insert (11 cm diameter) half filled with propylene glycol (Spence and Niemelä 1994). A plastic cover was placed approximately 2 cm above each trap to protect the trap from water and debris input and to reduce evaporation of trapping liquid. The traps were emptied every 7 – 14 days. The material in each trap was sieved through cheesecloth, and was preserved in 70% ethanol until beetles were sorted in the laboratory. The sorted material was stored in 70% ethanol. Carabids were identified to species using keys of Lindroth (1961-1969) and the reference collection at the Strickland Entomological Museum of the University of Alberta. Voucher collections were deposited at the Spence Laboratory Insect Collection of the University of Alberta, Edmonton, Alberta, Canada.

3.2.2.2. Weed Survey

Number of weed species and their abundance was surveyed using fifteen quadrats (0.5 m x 0.5 m) placed to form the shape of an inverted "w" on the surface of each plot before and after herbicide application (31 May and 24 July, 2000; 03 June and 24 July, 2003; 25 May and July 9, 2004; 4 June and 21 July, 2005). Data were expressed in terms of mean plant density (plants / m^2) for each plot.

3.2.3. *Analysis*

Species that could not be distinguished morphologically were pooled for analysis so that all specimens were retained for at least general analyses. The taxon *Amara carinata* (LeConte, 1848) also included *Amara lacustris* LeConte, 1855 and *Amara torrida* (Panzer, 1797), and *Harpalus funerarius* (Csiki, 1932) also included *Harpalus fraternus* LeConte, 1852. Carabid catch from each pitfall trap was standardized for trapping effort (beetle per trap per day) by dividing the number of beetle per trapping days for each trap for each sampling dates. Due to the occasional losses of samples of both traps from the same plot at a specific sampling date, a standardized catch was obtained by dividing the standardized catch by the number of collection dates.

3.2.4. Diversity

Rarefaction analysis was applied to the data before standardization using the Vegan package (Jari et al. 2005) available for R software (R Development Core Team 2005). Rarefaction curves were obtained using 1000 permutations for each sub-sample. Rarefaction standardization based on individuals is recommended for standardizing species richness for trapping effort (McCune and Grace 2002). Average species richness, Shannon-Wiener ($H' = -\Sigma$ (proportion)*ln(proportion)) and Evenness ($J' = H'$/ln(species richness)) indices were measured for all plots using non-standardized catch rate. ANOVA was performed on each diversity index using crop and input as model factors for each year. Tukey's HSD *post hoc* ($P < 0.05$) test was used to detect pair-wise differences.

3.2.5. Species Composition

Non-metric multidimensional scaling (NMDS) analysis was used to compare the species composition among treatments. In an NMDS ordination plot, distance between data points is directly proportional to species compositional dissimilarity (McCune and Grace 2002). Sorensen (Bray-Curtis) distances were used to calculate the dissimilarity matrix. The starting coordinates of the graphic were randomly selected. Forty runs with a maximum of 400 iterations (i.e. steps to adjust the position of data points on the graph) were performed to approximate the best graphical configuration. This process was initially done using six dimensions and reducing one dimension in each iteration cycle. For each dimension, the best configuration was chosen based on the lowest stress value. In

NMDS, the stress is a measure of mismatch of the data points presented in the ordination graph from the real data points. Low stress values indicates few distortions from the real position of the data points and thus the resulting NMDS graphs are more accurate representations of the dissimilarities in species composition. A preferred number of dimensions is suggested by the software when addition of an extra axis does not reduce stress value by more than five. A Monte Carlo probability is then calculated to evaluate if the final stress is lower than 95% of the 50 runs using random data.

The similarity in species composition among the crop, input and treatment was tested using multi-response permutation procedures (MRPP). MRPP is the non-parametric equivalent of MANOVA (multivariate analysis of variance); the procedure uses Sorensen (Bray-Curtis) distances to calculate the variation within (*A* value) and between groups (*T* value) and evaluates the probability of these groups to be similar (McCune and Grace 2002). The more negative the *T* value is, the stronger the separation between the groups compared is, and the closer the *A* value is to 1.0, the more homogenous the group is. Additionally, species vectors were calculated with a minimum r^2 of 0.3. The angle of the vector indicates the direction of the relationship with the ordination while the length indicates the strength

3.2.6. Indicator Species Analysis

Indicator species analysis (Dufrêne and Legendre 1997) was performed using PC-Ord (McCune and Mefford 1999) to test the association of carabid species to crop (wheat, potato or bean), inputs (sustainable or conventional) or treatments (an interaction between crop and input). I performed the analysis using the entire data set for each year. Indicator species analysis evaluates the relative frequency and relative catch of a single species in a given treatment and compares these with the pool of other treatments. Because a low number of individuals results in unreliable indicator values (McCune and Grace 2002), species with total catch less than 20 individuals were excluded from the analysis. The indicator measure ranges from 0 (lowest indicator) to 100 (highest indicator) and (in the software used) is calculated with an associated *p* value obtained from a Monte-Carlo test. This process ensured that a significant indicator is not selected by random chance.

3.2.7. Statistical Analysis

All the analyzed variables (beetle catch rates and weed density) were log $(x + 1)$ -transformed prior to analysis to meet the assumptions of the test at hand. Weed abundance from both surveys (before and after herbicide use) were summed prior to transformation. Year-specific sums of carabid and click beetle catches and weed abundance were analyzed using repeated measures ANOVA with the catch from each year as the dependent variable and rotation, input and interaction between these two as model factors. The samples from year 2000 were used as a model covariate to account for pre-treatment heterogeneity. Rotation was used as a model factor instead of crop type, because location of the crop changed every year and consequently the investigation of temporal effects would have been difficult (see Figure 10). Although rotation is the model factor, it is feasible to investigate the effect of crop type every year by determining which crop was present in each rotation at a specific year.

To investigate the effect of crop type and agronomic input on the catches of the numerically dominant carabid species, I performed a complete factorial MANOVA on the catch rate of the five most abundant species each year using crop type and agronomic input as independent factors for each year the treatments were applied, i.e., from 2003 to 2005. Only the five most abundant species were selected because in certain years, the low catch rate of certain species would have resulted in poor analysis power and unreliable conclusions. In 2005, despite the fact that *Poecilus lucublandus* (Say, 1823) was slightly more abundant than

Bembidion quadrimaculatum (Linné 1769), I used the latter in the analysis for the sake of consistency among years. The responses of individual species were tested using ANOVA following significant MANOVA (Wilk's Lambda P <0.05). In each analysis, Tukey's HSD *post hoc* ($P < 0.05$) test was used to find groupings. All statistical analyses were performed using SPSS 11.0 software (SPSS Inc. 1999).

3.3. Results

3.3.1. Carabid Fauna

A total of 12,813 carabids, representing 62 species from 22 genera, were collected during the four years of this study (one pre-treatment year and three years of applied treatments). The highest total catch and number of species were found in 2005 (3705 individuals and 49 species) and the lowest total and species richness were found in 2000 (2608 individuals and 41 species) (Appendix 2). The catch frequency varied between years for most species. *Pterostichus melanarius* (Illiger, 1798), a species introduced from Europe into North America, was the most abundantly collected species each year and produced 43[illegible]% of the total catch. In 2005 this species alone represented 60.9% of the total catch (Appendix 2). The peak activity for this species was in August. Other abundant carabid species caught over the four years were *Amara carinata* (9.5% of the total catch), *Amara farcta* LeConte, 1855 (7.6%), *Poecilus corvus* (LeConte, 1873) (6.1%), *Stenolophus comma* Say, 1823 (5.7%) and *Bembidion quadrimaculatum* (Linné, 1769) (5.3%). Over the four study years, 27 carabid species were represented by fewer than 10 specimens, and 12 were captured only once.

3.3.2. Diversity

Rarefaction analysis showed that carabid diversity varied among crops and treatments from year to year (Figure 11). Among the crops, the potato plots supported the highest carabid diversity in 2003 and in 2004 but had similar species richness to the other crops in other years (Figure 11, Appendix 3). Rarefaction curves also showed a lower diversity in wheat in 2000 and in 2003. Within the crop treatments, conventional wheat had higher carabid diversity than sustainable wheat in 2004 and in 2005. Sustainable bean plots produced higher carabid diversity than did conventional bean plots in 2004, but the pattern was opposite in 2005. For 2004 and 2005, the longer rarefaction curves in sustainable than in conventional wheat and bean plots simply indicate higher abundances in the former farming system. Diversity in sustainable and conventional potato plots was similar every year.

Diversity indices (Appendix 2) showed that species richness was significantly higher in sustainable than in conventional input plots, but only in 2003 ($F_{1,17} = 4.602$, $P = 0.047$). Shannon-Wiener indices did not differ significantly between crops, inputs and interaction term for any year. Evenness was significantly higher in potato than in bean or wheat plots, but again only in 2003 ($F_{2,17} = 6.238$, $P = 0.009$).

3.3.3. Species Composition

Crop type consistently influenced species composition each year (Figure 12). The carabid assemblages in bean and wheat plots differed from those of potato each year (MRPP analysis, Table 11), while the carabid assemblages in wheat significantly differed from those in bean plots only in 2000 and again in 2003. Species composition of sustainable and conventional potato plots was similar. However, sustainable bean plots produced a different carabid assemblage than conventional bean in 2003 and in 2005, while the species assemblages of sustainable and conventional wheat differed from each other in 2004 (Table 11). Species vectors associated with the ordination varied from year to year (Figure 12). However, *Pterostichus melanarius* vector was present each year and consistently pointed in the opposite direction of the potato plots. Vectors of *Agonum placidum* and *Harpalus amputatus* were associated mostly with wheat. The only species vector that showed strong association with potato plots was *Bembidion timidum* in 2003. No other species vectors were associated with that crop in any other year.

3.3.4. Indicator Species

Indicator species for crops, inputs or treatments varied among years (Table 12-15). Most indicators of specific crops were consistent for more than one year. *Poecilus corvus* and *Agonum placidum* were good indicators of wheat for three years, while *Amara farcta* was an indicator of wheat for two years. However, some species, such as *Bembidion rupicola* and *Amara carinata*, behaved inconsistently between years by being indicators of different treatments. *Amara farcta* was an indicator of sustainable wheat in 2003 and in 2004. Over the three treatment years (2003-2005), no species were indicators of conventional potato plots but *Bembidion timidum* and *Bembidion rupicola* were indicators of sustainable potato plots in 2003. Some species were significant indicators of the conventional input (Table 14).

3.3.5. Activity Density

Because two plots were not operational for more than one-half of the collecting season in 2005, concerns on the reliability of data led to the analysis performed with their exclusion. Table 15 shows the differences in results using both deleted and not deleted plots in the model. There was an overall effect of input on the total carabid catch when all the years were analyzed using a repeated measures design (between-subject: $F_{1,15} = 5.531$, $P = 0.033$) but no significant effects were found when years were analysed separately. Overall, the sustainable input plots had a higher carabid activity density than conventionally managed plots (

Table 16). The interaction between year and rotation (Crop type) had an effect on the activity density of carabids (year*rotation: $F_{4,30} = 10.891$, $P < 0.001$). Each year, potato plots accumulated lower catches than bean or wheat plots (2003: $F_{2,15} = 7.627$, $P = 0.005$; 2004: $F_{2,15} = 7.211$, $P = 0.006$; 2005: $F_{2,15} = 4.649$, $P = 0.027$;

Table 16).

From 2003-2005, input and crop type interacted to influence the activity density of the five most abundant species (2003: $F_{10,30} = 2.439$, $P = 0.031$; 2004: $F_{10,30} = 2.935$, $P = 0.012$; 2005: $F_{10,30} = 4.431$, $P = 0.001$;

Table 17). For two years, the activity density of *Amara farcta* was enhanced by the sustainable wheat (2003: $F_{2,18} = 8.268$, $P = 0.003$; 2004: $F_{2,18} = 5.783$, $P = 0.011$) while treatments in other crops had no influence on its activity density. In 2004, the activity density of *Bembidion quadrimaculatum* was increased by conventional beans and wheat while increased by sustainable potatoes ($F_{2,18} = 7.824$, $P = 0.004$). However, in 2005 only conventional beans increased it activity density ($F_{2,16} = 10.930$, $P = 0.001$). In 2003, the activity density of *Stenolophus comma* was increased by sustainable treatment in wheat ($F_{2,18} = 9.902$, $P = 0.001$). In 2005, the activity density of *Poecilus corvus* was increased by sustainable bean but slightly decreased by sustainable beans and potatoes ($F_{2,18} = 4.177$, $P = 0.032$).

3.3.6. Weed Density

There was an overall treatment effect (Between subject: $F_{1,15} = 22.769$, $P < 0.001$) and rotation (Between subject: $F_{2,15} = 5.085$, $P = 0.021$) on weed density (Figure 14). Year interacted with both rotation ($F_{4,30} = 10.255$, $P < 0.001$) and treatment ($F_{2,30} = 3.609$, $P = 0.036$). Agricultural input significantly affected weed density every year (2003: $F_{1,15} = 22.157$, $P = 0.001$; 2004: $F_{1,15} = 9.578$, $P < 0.001$ and 2005: $F_{1,15} = 4.566$, $P = 0.050$) while crop had an effect only in 2003 ($F_{2,15} = 12.009$, $P = 0.001$) and in 2004 ($F_{2,15} = 18.810$, $P < 0.001$). Sustainable input plots consistently had higher weed density (Figure 14). Wheat had the highest weed density in 2003, while in 2004 potato plots had the highest but were followed closely by wheat. No significant differences in weed density between crops were found in 2005.

3.3.7. Click Beetles

A total of 1139 adult elaterid beetles were capture from 2003 to 2005 (i.e. 211 in 2003, 552 in 2004 and 376 in 2005). Overall, sustainable input management significantly increased the activity density of click beetles only when catches were pooled over all years (Between subjects: $F_{1,15} = 5.914$, $P = 0.028$). When the catch rates for each plot were summed between years, sustainable treatment had an average of 0.052 ± 0.006 beetles per trap day, as opposed to 0.030 ± 0.005 in the conventional treatment. Crop type influenced the activity density of click beetles only on specific years (year*crop: $F_{4,30} = 10.856$, $P < 0.001$), where wheat had significantly higher elaterid capture in 2003 ($F_{2,15} = 4.546$, $P = 0.029$) and 2005 ($F_{2,15} = 11.103$, $P = 0.001$; Figure 15).

3.4. Discussion

The present study provides a synthesis of carabid responses to an alternative cropping system that includes less tillage and replacement of synthetic fertilizers with manure, as is characteristic of organic regimes. Relative to normal farm scales, the size of the experimental plots were small. Although pitfall catches in small plots may partly reflect inter-plot carabid movements, i.e., carabids caught in one plot may be wanderers from adjacent plots with different treatments (Butts et al. 2003), many studies have used relatively small plots to study successfully the effects of farming practices on carabids (Clark et al. 1993, Honek 1997, Raworth et al. 2004). I thus believe that despite this possible effect, the catches reliably reflect carabid habitat association.

3.4.1. Sustainable vs. Conventional Inputs

Contrary to my hypothesis and past results (Dritschilo and Erwin 1982, Cárcamo et al. 1995, Pfiffner and Niggli 1996, Bengtsson et al. 2005), the sustainable treatment did not consistently increase carabid diversity and had a minor role in producing a distinctive species composition. Thus, my results are more in line with those of several other workers (Holopainen 1983, Clark 1999, Melnychuk et al. 2003). This contrast in results begs for explanation. As mentioned by Purtauf et al. (2005), landscape structure may be important in explaining the carabid diversity found on farmland habitats. In the present study, the higher activity density of common carabids in sustainable wheat plots reduced the evenness of the community compared to the conventional wheat. However, the total and average number of species did not differ markedly between the two treatments in wheat. Thus, sustainably or conventionally grown wheat may not differ in ability to support different carabid species but sustainable wheat increases activity density of more common species such as *Amara farcta*. Similarity in carabid diversity between sustainably and conventionally grown potato has also been reported by Armstrong (1995), whereas Kromp (1990) reported higher diversity in plots with biological than in those with conventional potato. The presence of cover crop and narrower planting rows may have provided different micro-habitat structure throughout the season in bean plots, which may have favoured some species over others. For example, the absence of cover crop in conventional beans at the beginning of the year enhancec the activity density of *Bembidion quadrimaculatum* (in 2004 and 2005) while later in the season, *Amara carinata* preferred the conditions offered by the sustainable beans (in 2003 and 2004).

Consistently higher carabid catch in plots subject to sustainable treatment has been reported in earlier studies (Dritschilo and Wanner 1980, Cárcamo et al. 1995, Clark 1999). A possible explanation for this finding may be the augmentation of potential prey items following manure application, which may also be responsible in the observed increase weed density. Vegetation structure under organic or sustainable agriculture, as observed in my study, is more complex than under conventional agriculture and this, in turn, may support richer carabid assemblages (Andersen and Eltun 2000). Hence, sustainable inputs may provide more prey items – arthropods or weeds, depending on species – to carabids. Another factor possibly explaining the result may be tillage, especially with the mouldboard plough. This practice may have directly killed or injured carabids present at that time in conventional plots. Also, soils in plots under tillage are often characterized by lower moisture and higher temperature. Humidity and temperature are important factors explaining distribution and abundance of carabids (Rivard 1966, Honek 1997).

Some numerically dominant carabid species showed a response to the interaction between crop type and input, which demonstrates their sensitivity to variation in environmental conditions. Many species were also consistently most abundant in plots of a particular crop. The higher abundance of *Amara farcta* in sustainable wheat for two consecutive years (2003 and 2004) is probably due to higher weed abundance in both the sustainable treatment and wheat. Indeed, *Amara farcta* is often found among weeds (Lindroth 1961-1969). Additionally, the combination of lower crop and weed density may enhance the activity density of *Bembidion quadrimaculatum* in conventional bean plots. Because crops were rotated each year on the study site, the location of a specific crop varied among the study years. Thus, I suggest that in many of these fields, carabids re-colonize the more suitable habitats. This better explains variation in carabid catches than the possible effect of over-wintering of individuals within the experimental plots.

3.4.2. Effect of Crop Type

Plots with potato had consistently fewer carabids but not lower diversity than plots with wheat or bean plots. For example, the catches of *Pterostichus melanarius*, an introduced species, were less in potato plots. Being the most abundant species in this study (Appendix 2), the activity density of *P. melanarius* influenced the general pattern observed as the activity density of many other species did not seem to be consistently affected by potato cropping. These results can be explained mostly by the heavy application of insecticides, which likely lowered both the abundance of carabids and their available prey. Insecticide application has been shown to reduce carabid activity density (Sekulic et al. 1987). Also, the soil microtopography in potato fields is rather complex (compared to beans and wheat), being a series of alternating high (potato 'hills' where plants are located) and low (interrow furrow) areas. This microtopgraphy may act as a barrier for carabid dispersal. Additionally, the intensive soil preparation required to cultivate potatoes may also have induced direct mortality.

Even if bean and wheat plots generally had a similar overall carabid abundance, species composition differed between these two crops in two of the four years sampled. Differences in micro-habitat structure may explain most of this separation. Mature broadleaf dicots, such as bean and potato, produce a dense canopy compared to the canopy of wheat that remains more open throughout the season. Canopy structure can be important for thermoregulation of many species. Generally, open canopy provides drier and warmer environment that may favor xerophilous species. However, wheat and beans are also grown at different in plant density. Plant density was lower in bean than wheat plots, which potentially facilitated carabid movements among plants. I suggest that species associated with open habitat would be enhanced under low plant density. In fact, only small open-habitat associated species (such as *Bembidion quadrimaculatum* and *Bembidion timidum*) appeared indicators of potato and bean plots. On the other hand, species like *Amara farcta* are often found among weeds (Lindroth 1961-1969) and were more abundant in wheat in the present study. Other species such as *Agonum placidum* and *Poecilus corvus* were associated with wheat probably for the same reason.

3.4.3. Click Beetles and Carabids

Each year, the number of click beetles caught was higher under sustainable than under conventional treatment. Also, it appears that generally more click beetles were caught in wheat than in potato or beans were lower. Elaterids have been shown to be attracted to wheat (Doane et al. 1975, Vernon et al. 2000).

It is difficult to assess the importance of carabid beetles in managing populations of click beetles based on the present study, mainly because the adult click beetles are not pests. Some species of carabids, like *Clivina fossor* and species of the genus *Pterostichus* prey on the wireworms (Holland 2002) but very little is known about the interactions between carabid and click beetle populations. Also, since carabid larvae are generally active in the soil, they are more likely to encounter and eat wireworms. Intuitively, a larger population of adult click beetles, as found in the sustainable treatment would generate a larger population of larvae. However, larger populations of carabids should similarly increase predation rate on the wireworms.

3.5. Conclusions

This study showed that agronomic practices commonly associated with sustainable agriculture do not necessarily increase carabid diversity but that they seem to promote a higher activity density. Increasing carabid activity and, presumably abundance, may be significant for the natural biological control of arthropod crop pests and, thus, a component of a more environmentally friendly pest management strategy. However, the sustainable treatment also promoted rather high activity density of adult click beetles, the larvae of which are significant pests of wheat on the Canadian prairies. It remains unclear if the increased activity of carabids in the sustainable treatment may regulate or help regulate click beetle populations at a certain level below the economic threshold. Crop type had a major influence in shaping the composition of carabid assemblages, while agronomic inputs had only weak effects on species composition. The potato crop appeared to be a less favorable for carabid abundance, although this likely resulted from pesticide applications and the intensive farming operations required throughout the season. Regarding pest management strategies, the present study suggests that rotation of potatoes with beans and/or wheat is an efficient means for maintaining farmland assemblages and populations of carabids. The application of organic soil amendments (e.g. compost, manure) and reduction of tillage also contribute to the maintenance of carabid assemblages, but these practices may increase wireworm problems, as recently reported by potato growers in southern Alberta.

List of Tables

Table 6: Studied treatments with respective agronomic operations.

Rotation	Input	Crop	Variety	Fertilizer	Plant density (plant / m^2)	Cover crop
1	Conventional	Potato	Russet Burbank	134 N, 67 P, 67 K kg/ha fall	3.6	No
2	Conventional	Bean	AC Red Bond (2003 UI906)	90 kg/ha N spring	26	No
3	Conventional	Wheat	Soft White Spring Wheat AC Reed	90 kg/ha N spring	322	No
1	Sustainable	Potato	Russet Burbank	62 N, 28 P, 67 K (28 t/ha compost fall)	3.6	No
2	Sustainable	Bean	AC Red Bond (2003 UI906)	90 kg/ha N spring	43	Yes
3	Sustainable	Wheat	Soft White Spring Wheat AC Reed	90 kg/ha N spring	322	Yes

Table 7: Herbicide applications for each crop and year.

Year	Crop	Product	Active ingredient	Application rate (g ai/ha)	Date
2000	Bean	Edge DC	Ethalfluralin	1142	11 May
		Poast Ultra	Sethoxydim	495	14 June
		Basagram	Bentazon	1079	18 June
		Reglone	Diquat Dibromide	890	7 Sept
	Potato	Eptam	EPTC	5930	20 April
		Reglone*	Diquat Dibromide	880	1 Sept
	Wheat	Achieve Extra Gold	Tralkoxydin	217	30 May
		Buctril M	Bromoxynil, MCPA	277 each	30 May
		Reglone	Diquat Dibromide	890	15 August
2003	Bean	Edge DC	Ethalfluralin	1142	10 Oct 2002
		Roundup*	Glyphosate	880	20 May
		Basagram	Bentazon	1079	17 June
		Poast Ultra	Sethoxydim	495	27 June
		Poast Ultra*	Sethoxydim	495	8 July
	Potato	Sencor 75DF	Metribuzin	278	25 June
		Reglone	Diquat Dibromide	593	2 Sept
	Wheat	Achieve extra gold	Tralkoxydin	217	3 June
		Buctril M	Bromoxynil, MCPA	277 each	3 June
		Reglone	Diquat Dibromide	593	2 Sept
2004	Bean	Roundup*	Glyphosate	880	13 May
		Edge DC	Ethalfluralin	1142	14 May
		Basagram	Bentazon	1079	17 and 29* June
		Poast Ultra	Sethoxydim	495	19 June
		Reglone*	Diquat Dibromide	593	4 Sept
	Potato	Sencor 75DF	Metribuzin	278	10 June
		Reglone	Diquat Dibromide	593	27 August
	Wheat	Target	MCPA, mecoprop,dicamba	407, 93, 93	26 May
		Horizon	Clodinafop propargyl	56	26 May
		Puma super	Fenoxaprop-p-ethyl	46	3 June
		Roundup*	Glyphosate	880	13 Sept
2005	Bean	Roundup*	Glyphosate	880	4 May
		Edge**	Ethalfluralin	1142	12 May
		Basagram	Bentazon	1079	27 June, 4 and 21 July
		Poast Ultra	Sethoxydim	495	7 July
		Reglone	Diquat Dibromide	593	20 Sept
	Potato	Roundup***	glyphosate	880	7 July
		Sencor 75DG	Metribuzin	278	8 July
		Roundup***	Glyphosate	880	15 August
		Reglone	Diquat Dibromide	593	26 August
	Wheat	Horizon	Clodinafop propargyl	56	1 June, 16 June
		Target	MCPA, mecoprop,dicamba	407,93,93	1 June,16 June

* only applied on sustainable treatment.

** only applied on conventional treatment.

*** only applied in one sustainable and in one conventional plot to terminate potato growing.

Table 8: Insecticide application in potato plots for each year.

Year	Product	Active ingredient	Insecticide class	Application rate (g ai/ha)	Date
2000	Cymbush	Cypermethrin beta	Pyrethroid	99	7 July
	Cymbush	Cypermethrin beta	Pyrethroid	50	17 July
	Monitor	Methamidophos	organophosphorous	950	1 August
2003	Monitor	Methamidophos	organophosphorous	950	12, 24 June
	Monitor	Methamidophos	organophosphorous	950	7 July
	Monitor	Methamidophos	organophosphorous	950	11, 25 August
2004	Lorsban 4E	Chloryrifos	organophosphorous	474	11 June
	Monitor	Methamidophos	organophosphorous	950	16 June
	Cymbush	Cypermethrin beta	Pyrethroid	33	30 June
	Monitor	Methamidophos	organophosphorous	950	16, 29 July
2005	Monitor	Methamidophos	organophosphorous	950	15 June, 29 July
	Admire	Imidacloprid	Chloronicotinyl	47	18 June
	Admire	Imidacloprid	Chloronicotinyl	30	15 August

Table 9: Fungicide application for each crop and year.

Year	Crop	Product	Active ingredient	Application rate (g ai/ha)	Date
2000	Bean	Kocide	Copper hydroxyde	2802	20 June
		Kocide	Copper hydroxyde	2802	6, 17 July
		Ronalin	Vinclozolin	504	28 July
	Potato	Bravo	Chlorothalonil	988	21 June
		Bravo	Chlorothalonil	988	7, 19 July
		Ridomil Gold	Mancozeb, Metalaxyl	1581, 198	28 July, 11 Aug
2003	Bean	Kocide	Copper hydroxyde	2802	27 June
		Kocide	Copper hydroxyde	2802	8, 10 July
		Ronalin	Vinclozolin	741	25 July
	Potato	manzate	Maneb	1280	25 June
		curzate	Cymoxanil	135	25 June
		Bravo	Chlorothalonil	988	11 July
		Bravo	Chlorothalonil	988	11, 25 August
2004	Bean	Kocide	Copper hydroxyde	2802	30 June, 19 July
		Lance	Boscalid	432	30 July, 11 Aug
		Parasol	Copper Hydroxide	3088	12 August
	Potato	Bravo	Chlorothalonil	988	16, 30 June
		Bravo	Chlorothalonil	988	16,29 July
2005	Bean	Parasol	Copper Hydroxide	1235	27 June; 4, 22 July; 8 August
		Lance	Boscalid	518	29 July
	Potato	Bravo	Chlorothalonil	988	15 June, 29 July
		Ridomil Gold	Metalalxyl	14	19 July
		Bravo	Chlorothalonil	7	19 July

Table 10: Parameters associated with NMDS ordination for the carabid community for each year.

Year	Iterations	Stress	Monte Carlo *P*	Axis 1 R^2	Axis 2 R^2	R^2 cumulative
2000	33	18.174	0.0392	0.306	0.409	0.735
2003	71	10.517	0.0196	0.304	0.463	0.767
2004	146	12.526	0.0392	0.258	0.624	0.882
2005	68	11.287	0.0196	0.739	0.120	0.859

Table 11: Significant ($P < 0.05$) MRPP comparisons between crops and treatments for each study year.

Year	Comparison	*T*	*A*	*P*
2000	Wheat vs. Potato	-5.59	0.14	< 0.001
	Bean vs. Potato	-2.11	0.05	0.046
	Bean vs. Wheat	-3.05	0.07	0.011
2003	Wheat vs. Potato	-7.25	0.02	< 0.001
	Bean vs. Potato	-5.126	0.12	0.001
	Bean vs. Wheat	-2.21	0.05	0.032
	Sust. vs Conv. Beans	-2.39	0.11	0.021
2004	Wheat vs. Potato	-3.92	0.07	0.005
	Bean vs. Potato	-2.64	0.04	0.017
	Sust. vs Conv. Wheat	-2.16	0.08	0.028
2004	Wheat vs. Potato	-2.11	0.05	0.039
	Bean vs. Potato	-4.13	0.10	0.003
	Sust. vs. Conv. Bean	-3.79	0.29	0.008

Table 12: Significant indicator species of different crops.

	Species	Crop	Number collected	Indicator value	*P*
2000	*Bembidion quadrimaculatum*	Bean	145	58.2	0.041
	Agonum cupreum	Wheat	51	94.0	0.001
	Poecilus lucublandus	Wheat	293	61.4	0.001
	Agonum placidum	Wheat	285	80.1	0.001
	Poecilus corvus	Wheat	230	62.3	0.013
2003	*Amara quenseli*	Bean	29	57.6	0.020
	Bembidion timidum	Potato	77	80.3	0.001
	Amara farcta	Wheat	365	77.8	0.003
	Stenolophus comma	Wheat	305	82.5	0.006
	Poecilus corvus	Wheat	27	55.3	0.022
2004	*Bembidion obscurellum*	Bean	68	71.9	0.010
	Bembidion timidum	Bean	90	51.0	0.029
	Agonum placidum	Wheat	64	72.2	0.001
	Poecilus corvus	Wheat	288	63.8	0.004
	Amara farcta	Wheat	361	72.8	0.021
	Harpalus amputatus	Wheat	31	49.4	0.040
2005	*Agonum placidum*	Wheat	55	63.4	0.024

Table 13: Significant indicator species of treatments.

	Species	Treatment	Number collected	Indicator value	*P*
2003	*Amara apricaria*	Bean sustainable	47	70.1	0.004
	Amara quenseli	Bean sustainable	29	49.3	0.013
	Amara carinata	Bean sustainable	655	52.9	0.036
	Bembidion rupicola	Potato sustainable	24	72.6	0.002
	Bembidion timidum	Potato sustainable	77	46.5	0.011
	Stenolophus comma	Wheat sustainable	305	82.9	0.001
	Amara farcta	Wheat sustainable	365	67.0	0.001
2004	*Bembidion obscurellum*	Bean conventional	68	60.6	0.003
	Bembidion rupicola	Wheat conventional	22	40.2	0.027
	Amara farcta	Wheat sustainable	361	65.4	0.028
	Poecilus lucublandus	Wheat sustainable	122	35.6	0.043
	Harpalus amputatus	Wheat sustainable	31	42.6	0.048
	Agonum cupreum	Wheat sustainable	21	39.8	0.049
2005	*Bembidion quadrimaculatum*	Bean conventional	82	44.0	0.006
	Poecilus corvus	Bean sustainable	246	31.4	0.011
	Amara carinata	Wheat sustainable	27	42.1	0.019

Table 14: Significant indicator species of sustainable and conventional inputs.

	? Species	Input	Number collected	Indicator value	P
2003	*Amara farcta*	Sustainable	365	82.9	0.006
	Stenolophus comma	Sustainable	305	72.9	0.016
	Amara apricaria	Sustainable	47	63.9	0.021
2004	*Agonum cupreum*	Sustainable	21	64.3	0.010
	Bembidion obscurellum	Conventional	68	70.7	0.014
	Amara carinata	Sustainable	267	76.7	0.023
2005	*Bembidion obscurellum*	Conventional	54	64.9	0.027
	Bembidion quadrimaculatum	Conventional	82	66.3	0.048

Table 15: ANOVA table with repeated measure (Between subject) showing results when two potato plots were deleted from the model due to a very low trapping period (see text)

Without deletion of potato plots

Source	*SS*	*df*	*MS*	*F*	*P*
Input	0.046	1	0.046	3.374	0.084
Rotation	0.003	2	0.002	0.119	0.889
Input*Rotation	0.020	2	0.01	0.741	0.491
Year 2000	0.034	1	0.034	2.509	0.132
Error	0.232	17	0.014		

With deletion of potato plots

Source	*SS*	*df*	*MS*	*F*	*P*
Input	0.056	1	0.056	5.531	0.033
Rotation	0.027	2	0.014	1.334	0.293
Input*Rotation	0.031	2	0.015	1.514	0.252
Year 2000	0.013	1	0.013	1.307	0.271
Error	0.153	15	0.010		

Table 16: Mean activity density (specimens / trap * day) of the five most abundant carabid species and total carabid abundance in three crops (*n* = 8, ± 1 S.E. , except potato in 2005 where n = 6) and two input levels (*n* = 12, ± 1 S.E. , except in sustainable in 2005 where n = 10). Letters indicate results from pair-wise comparisons (Tukey's $P < 0.05$) following a significant result in ANOVA.

Carabid species	Crop			Input	
2003	Bean	Potato	Wheat	Conventional	Sustainable
Amara carinata	0.359 ± 0.138	0.021 ± 0.006	0.200 ± 0.152	0.152 ± 0.102	0.234 ± 0.103
Stenolophus comma	0.007 ± 0.003	0.003 ± 0.002	0.194 ± 0.072	0.017 ± 0.012	0.120 ± 0.055
Amara farcta	0.049 ± 0.014	0.016 ± 0.004	0.230 ± 0.082	0.033 ± 0.010	0.164 ± 0.061
Pterostichus melanarius	0.360 ± 0.114	0.075 ± 0.030	0.372 ± 0.074	0.299 ± 0.074	0.239 ± 0.077
Bembidion quadrimaculatum	0.054 ± 0.011	0.048 ± 0.010	0.032 ± 0.006	0.039 ± 0.007	0.051 ± 0.007
Total carabids	1.025 ± 0.265 a	0.288 ± 0.053 b	1.188 ± 0.272 a	0.683 ± 0.199	0.985 ± 0.215
2004					
Amara carinata	0.090 ± 0.055	0.032 ± 0.007	0.041 ± 0.012	0.025 ± 0.006	0.083 ± 0.036
Poecilus corvus	0.039 ± 0.008	0.031 ± 0.010	0.126 ± 0.040	0.056 ± 0.013	0.076 ± 0.030
Amara farcta	0.044 ± 0.017	0.029 ± 0.009	0.199 ± 0.094	0.049 ± 0.012	0.132 ± 0.067
Pterostichus melanarius	0.320 ± 0.084	0.122 ± 0.031	0.257 ± 0.046	0.221 ± 0.048	0.245 ± 0.056
Bembidion quadrimaculatum	0.071 ± 0.014	0.041 ± 0.009	0.083 ± 0.012	0.077 ± 0.013	0.054 ± 0.006
Total carabids	0.817 ± 0.116 ab	0.466 ± 0.103 b	1.018 ± 0.183 a	0.640 ± 0.082	0.895 ± 0.156
2005					
Amara carinata	0.045 ± 0.008	0.037 ± 0.009	0.089 ± 0.038	0.044 ± 0.008	0.070 ± 0.026
Poecilus corvus	0.094 ± 0.019	0.059 ± 0.012	0.050 ± 0.011	0.064 ± 0.009	0.070 ± 0.015
Amara farcta	0.026 ± 0.011	0.070 ± 0.027	0.100 ± 0.035	0.073 ± 0.023	0.057 ± 0.023
Pterostichus melanarius	0.660 ± 0.127	0.206 ± 0.045	0.671 ± 0.228	0.430 ± 0.149	0.595 ± 0.122
Bembidion quadrimaculatum	0.037 ± 0.014	0.026 ± 0.009	0.018 ± 0.004	0.040 ± 0.010	0.015 ± 0.003
Total carabids	1.046 ± 0.106 a	0.531 ± 0.048 b	1.099 ± 0.196 a	0.835 ± 0.141	0.949 ± 0.116

Table 17: Mean activity density of the five most abundant carabid species and the total carabid in treatments (*n* = 4, ± 1 S.E., except potato in 2005 where n = 3). Significant differences are indicated with * for $P < 0.05$ and ** for $P < 0.01$.

Carabid Species	Bean		Potato		Wheat	
2003	Conventional	Sustainable	Conventional	Sustainable	Conventional	Sustainable
Amara carinata	0.103 ± 0.031	0.615 ± 0.210	0.021 ± 0.012	0.020 ± 0.007	0.333 ± 0.310	0.068 ± 0.028
Stenolophus comma	0.003 ± 0.001	0.012 ± 0.004	0.001 ± 0.001	0.006 ± 0.004	0.046 ± 0.035	0.342 ± 0.094**
Amara farcta	0.025 ± 0.012	0.073 ± 0.020	0.011 ± 0.005	0.021 ± 0.006	0.063 ± 0.023	0.397 ± 0.113**
Pterostichus melanarius	0.375 ± 0.136	0.345 ± 0.206	0.101 ± 0.058	0.049 ± 0.024	0.422 ± 0.137	0.322 ± 0.071
Bembidion quadrimaculatum	0.036 ± 0.009	0.072 ± 0.016	0.052 ± 0.021	0.044 ± 0.003	0.029 ± 0.004	0.036 ± 0.012
Total carabids	0.646 ± 0.195	1.404 ± 0.440	0.301 ± 0.104	0.275 ± 0.047	1.101 ± 0.529	1.274 ± 0.248
2004						
Amara carinata	0.030 ± 0.011	0.150 ± 0.107	0.022 ± 0.012	0.041 ± 0.007	0.023 ± 0.009	0.059 ± 0.020
Poecilus corvus	0.040 ± 0.017	0.039 ± 0.002	0.038 ± 0.021	0.025 ± 0.006	0.089 ± 0.023	0.163 ± 0.077
Amara farcta	0.069 ± 0.032	0.020 ± 0.005	0.037 ± 0.019	0.020 ± 0.003	0.040 ± 0.008	0.357 ± 0.158*
Pterostichus melanarius	0.333 ± 0.095	0.307 ± 0.155	0.085 ± 0.036	0.159 ± 0.047	0.246 ± 0.071	0.268 ± 0.068
Bembidion quadrimaculatum	0.103 ± 0.013	0.038 ± 0.008**	0.025 ± 0.006	0.058 ± 0.015	0.102 ± 0.021	0.065 ± 0.008
Total carabids	0.777 ± 0.063	0.858 ± 0.240	0.450 ± 0.218	0.482 ± 0.046	0.693 ± 0.056	1.343 ± 0.288
2005						
Amara carinata	0.053 ± 0.012	0.037 ± 0.010	0.046 ± 0.016	0.027 ± 0.008	0.034 ± 0.017	0.145 ± 0.067
Poecilus corvus	0.060 ± 0.020	0.127 ± 0.023*	0.068 ± 0.016	0.049 ± 0.019	0.066 ± 0.016	0.034 ± 0.012
Amara farcta	0.044 ± 0.017	0.007 ± 0.007	0.043 ± 0.026	0.097 ± 0.047	0.131 ± 0.056	0.069 ± 0.046
Pterostichus melanarius	0.387 ± 0.084	0.932 ± 0.140	0.194 ± 0.065	0.217 ± 0.072	0.707 ± 0.434	0.635 ± 0.232
Bembidion quadrimaculatum	0.073 ± 0.009	0.001 ± 0.001**	0.034 ± 0.018	0.019 ± 0.003	0.012 ± 0.006	0.025 ± 0.006
Total carabids	0.866 ± 0.075	1.226 ± 0.161	0.526 ± 0.015	0.536 ± 0.104	1.111 ± 0.396	1.087 ± 0.150

List of Figures

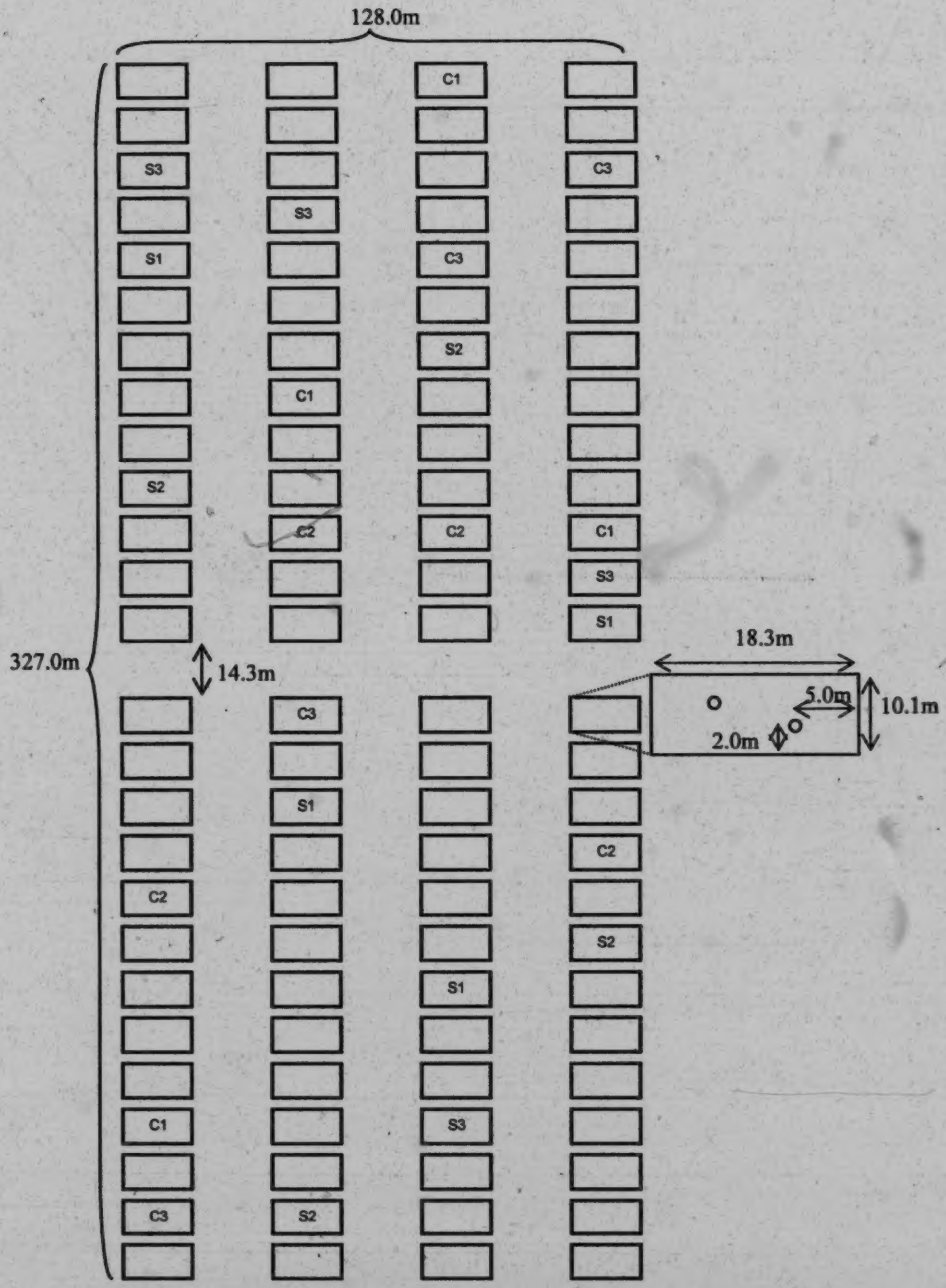
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Figure 10: Study site, plot dimensions and pitfall trap positions (S = sustainable, C = conventional treatment). Numbers represent rotation cycles starting with specific crops as follows: 1 = Potato, 2 = Bean and 3 = Wheat. Circles show the position of traps within an experimental plot.

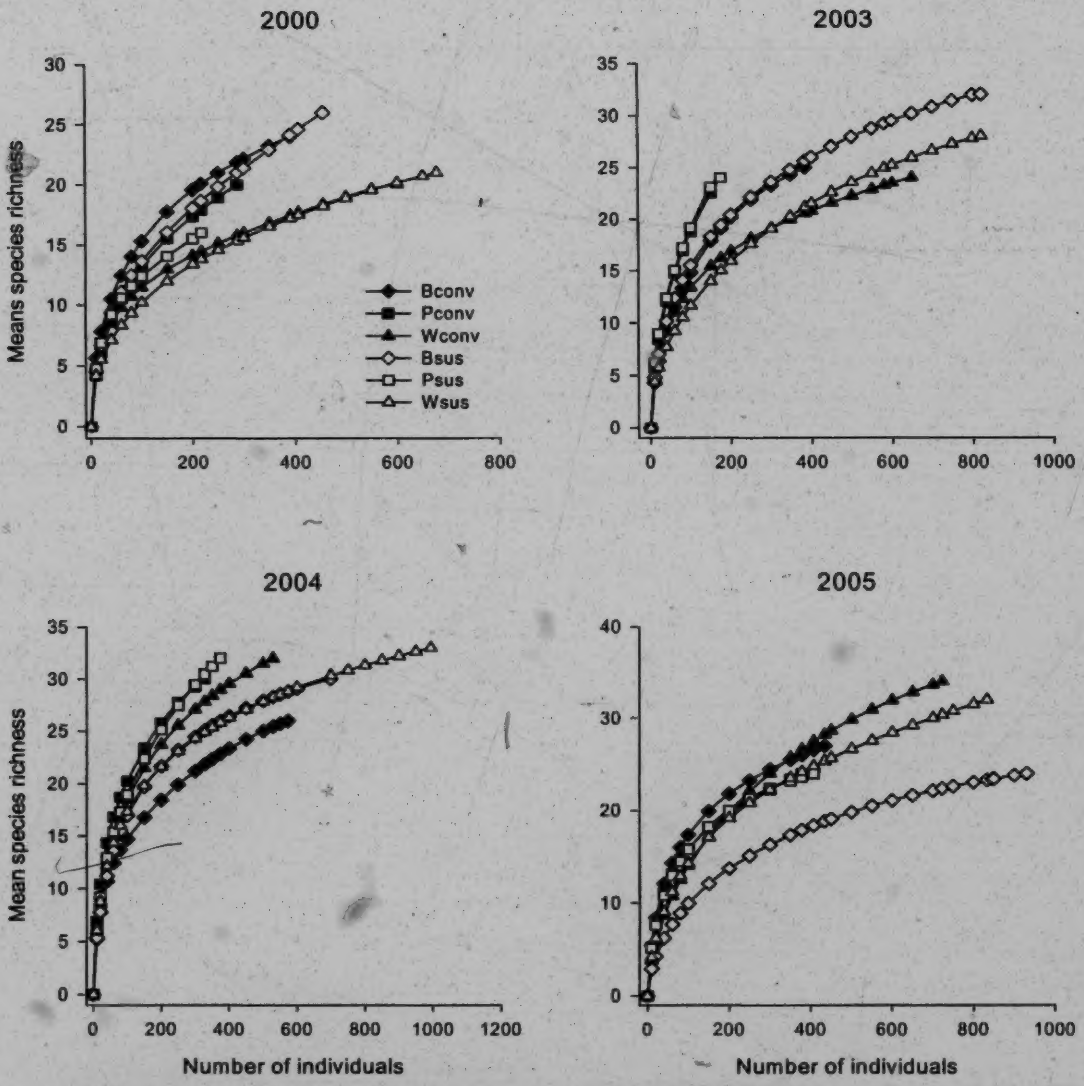

Figure 11: Species accumulation curves for each crop species and input level. Selection of sub-samples of individuals was done randomly and, except for the last one, reached maximum of individuals caught. Legend reads.: P = potato, B = beans and W = Wheat, followed by conv = conventional and sus = sustainable.

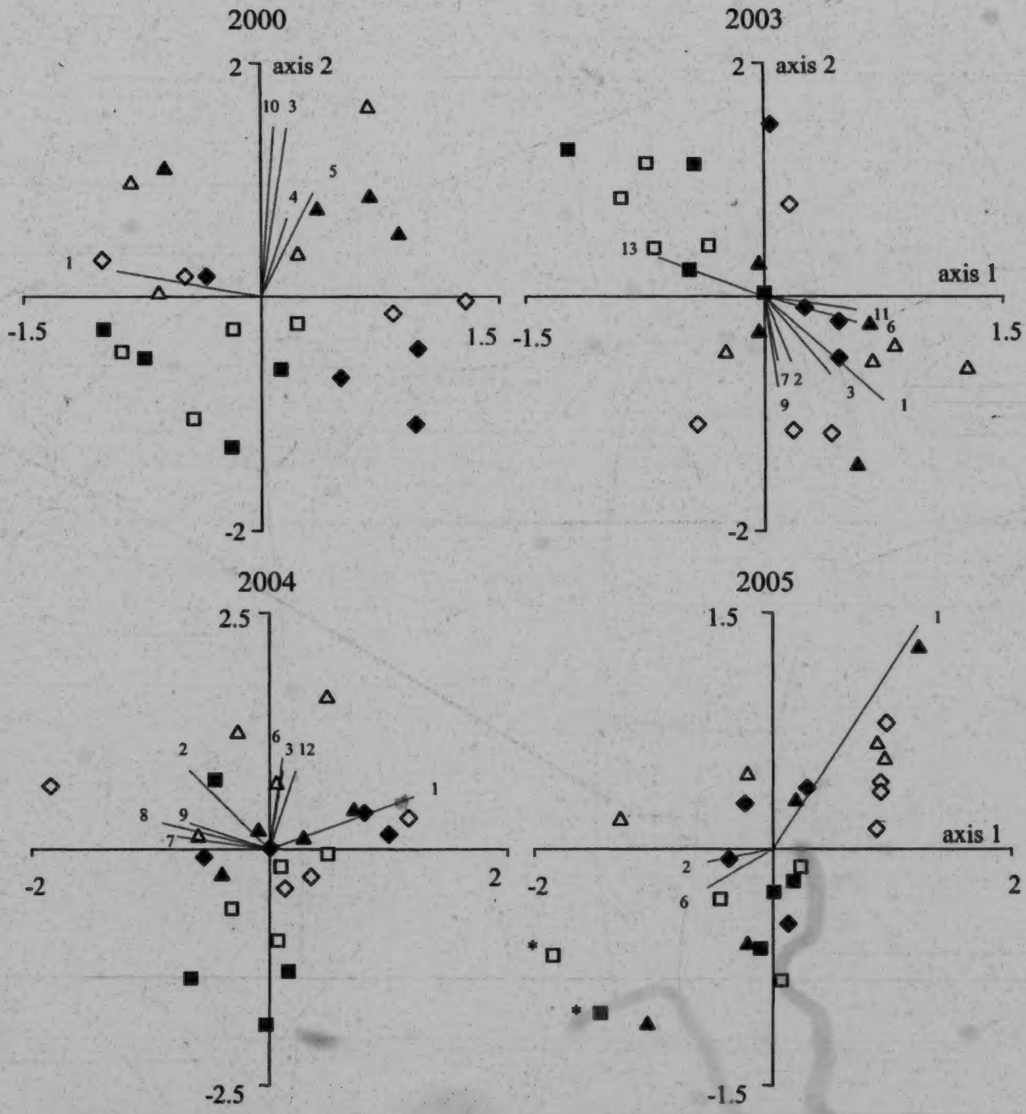

Figure 12: Non-metric multidimensional scaling (NMDS) ordination for the carabid assemblages, done separately for each year to demonstrate systematic variation among crop species. Note that input treatments were not applied in 2000. Symbols show treatments as follows: ◊ = Bean, □ = potato, Δ - wheat. Black (solid) symbols indicate conventional and White (hollow) ones sustainable treatment. Vectors (minimum r^2 of 0.3) show the NMDS scores for different species as follows. 1: *P. melanarius*, 2: *H. amputatus*, 3: *A. placidum*, 4: *A. cupreum*, 5: *P. corvus*, 6: *Amara farcta*, 7: *Am. quenseli*, 8: *H. funerarius*, 9: *Am. carinata*, 10: *P. lucublandus*, 11: *S. comma*, 12: *Am. littoralis* and 13: *B. timidum*. * indicates plots that were operational for less than half of the sampling period.

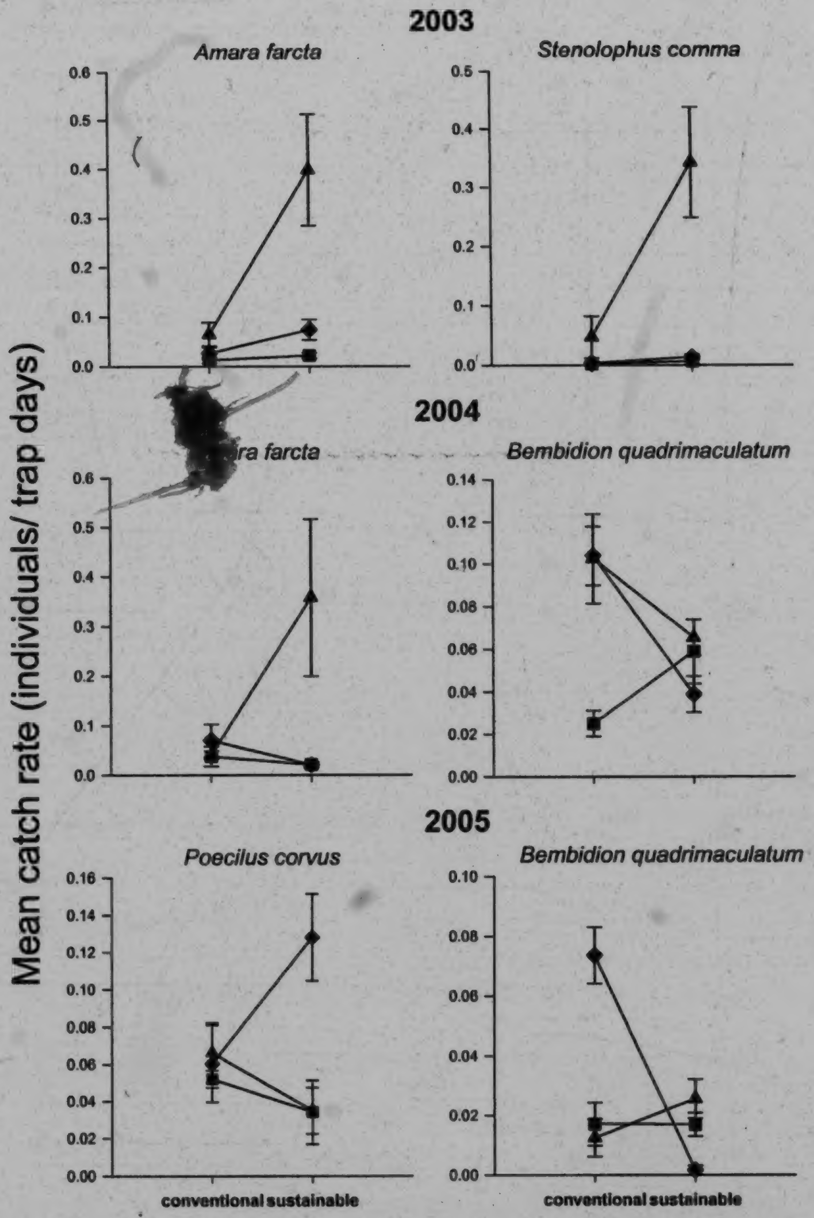

Figure 13: Mean activity density of carabid species showing a significant response to the interaction between crop and input. (*n*=4, ± 1 S.E except potatoes in 2005 where *n* = 3)

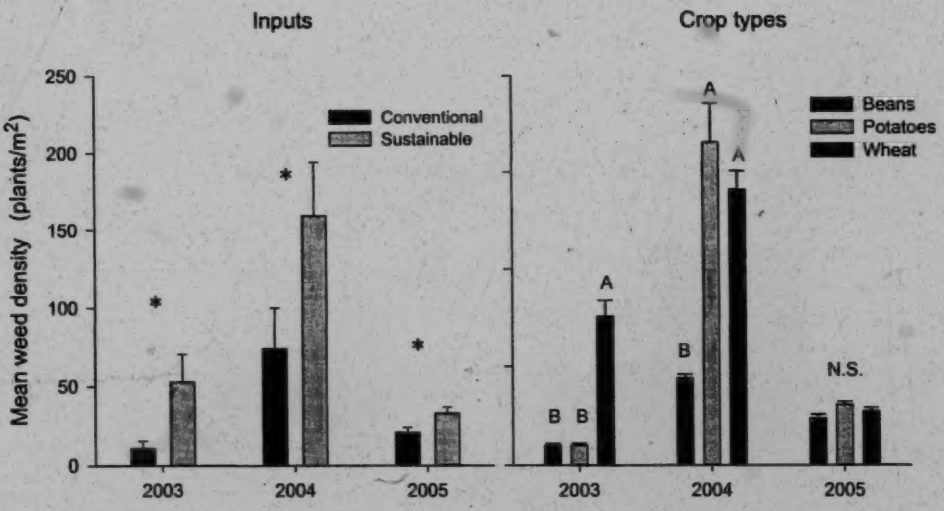

Figure 14: Average weed density in different inputs (*n* = 12, ± 1 S.E.) and crop types (*n* = 8, ± 1 S.E.) for the three post-treatment years. * indicates that a significant difference ($P < 0.05$) was detected each year between sustainable and conventional inputs (left). Letters represent differences among the crop species, within respective years, following a significant ANOVA result (Tukey's test, $P < 0.05$).

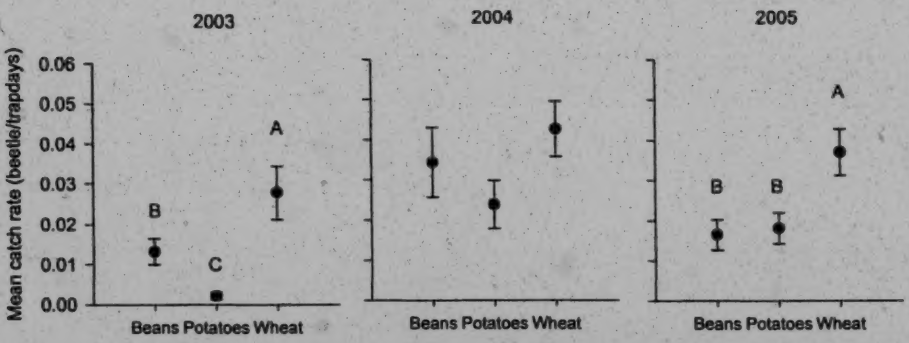

Figure 15: Mean catch rates (with S.E.) of elaterid beetles in different crop (*n* = 8, except potatoes 2005 n = 6). Letters indicate significant pair-wise differences detected after a significant ANOVA result (Tukey's test, *P* < 0.05).

Appendices

Appendix 2: Count (C) and frequency (F) of carabid species caught in each study year, and pooled total numbers.

	2000		2003		2004		2005		Total	
Carabid Species	C	F	C	F	C	F	C	F	C	F
Pterostichus melanarius (Illiger, 1798)	1158	44.4	928	30.89	1178	33.7	2257	60.92	5521	43.09
Amara carinata (LeConte, 1848)	30	1.15	655	21.8	267	7.64	271	7.31	1223	9.54
Amara farcta LeConte, 1855	14	0.54	365	12.15	361	10.33	228	6.15	968	7.55
Poecilus corvus (LeConte, 1873)	230	8.82	27	0.9	288	8.24	246	6.64	791	6.17
Stenolophus comma (Fabricius, 1775)	195	7.48	305	10.15	176	5.03	50	1.35	726	5.67
Bembidion quadrimaculatum (Linné 1769)	145	5.56	182	6.06	262	7.49	82	2.21	671	5.24
Poecilus lucublandus (Say, 1823)	293	11.23	22	0.73	122	3.49	97	2.62	534	4.17
Agonum placidum (Say, 1823)	285	10.93	30	1	64	1.83	55	1.48	434	3.39
Harpalus funerarius Mannerheim, 1853	7	0.27	76	2.53	157	4.49	21	0.57	261	2.04
Bembidion timidum (LeConte, 1848)	32	1.23	77	2.56	90	2.57	28	0.76	227	1.77
Harpalus herbivagus Say, 1823	22	0.84	16	0.53	110	3.15	68	1.84	216	1.69
Bembidion obscurellum (Motschulsky, 1845)	9	0.35	52	1.73	68	1.95	54	1.46	183	1.43
Amara apricaria (Paykull, 1790)	5	0.19	47	1.56	23	0.66	37	1.00	112	0.87
Microlestes linearis (LeConte, 1851)	7	0.27	9	0.3	86	2.46	4	0.11	106	0.83
Agonum cupreum Dejean, 1831	51	1.96	1	0.03	21	0.60	17	0.46	90	0.70
Harpalus amputatus Say, 1830	13	0.5	21	0.7	31	0.89	20	0.54	85	0.66
Bembidion rupicola (Kirby, 1837)	17	0.65	24	0.8	22	0.63	19	0.51	82	0.64
Amara torrida (Panzer, 1797)	21	0.81	26	0.87	12	0.34	2	0.05	61	0.48
Bembidion nitidum (Kirby, 1837)	2	0.08	9	0.3	14	0.40	31	0.84	56	0.44
Amara quenseli (Schönherr, 1806)	—	—	29	0.97	15	0.43	10	0.27	54	0.42
Agonum corvus (LeConte, 1860)	1	0.04	17	0.57	16	0.46	12	0.32	46	0.36
Pterostichus femoralis (Kirby, 1837)	35	1.34	5	0.17	3	0.09	1	0.03	44	0.34
Amara latior (Kirby, 1837)	1	0.04	17	0.57	8	0.23	3	0.08	29	0.23
Harpalus fraternus LeConte, 1852	1	0.04	1	0.03	4	0.11	19	0.51	25	0.20
Harpalus paratus Casey, 1924	5	0.19	5	0.17	11	0.31	4	0.11	25	0.20
Calosoma obsoletum Say, 1823	—	—	4	0.13	5	0.14	15	0.40	24	0.19
Pterostichus adstrictus Eschscholtz, 1823	4	0.15	2	0.07	10	0.29	4	0.11	20	0.16
Amara littoralis Mannerheim, 1843	2	0.08	8	0.27	2	0.06	7	0.19	19	0.15
Amara lacustris LeConte, 1855	5	0.19	6	0.2	5	0.14	—	—	16	0.12
Harpalus ventralis LeConte, 1848	1	0.04	—	—	13	0.37	2	0.05	16	0.12
Bembidion bimaculatum (Kirby, 1837)	2	0.08	9	0.3	1	0.03	3	0.08	15	0.12
Bradycellus congener (LeConte, 1848)	2	0.08	5	0.17	5	0.14	2	0.05	14	0.11
Amara obesa (Say, 1823)	1	0.04	2	0.07	5	0.14	6	0.16	14	0.11
Harpalus fuscipalpis Sturm, 1818	—	—	6	0.2	6	0.17	—	—	12	0.09
Poecilus scitulus LeConte, 1848	2	0.08	2	0.07	2	0.06	5	0.13	11	0.09
Bembidion castor Lindroth, 1963	—	—	6	0.2	—	—	3	0.08	9	0.07
Calathus ingratus Dejean, 1828	2	0.08	—	—	6	0.17	1	0.03	9	0.07
Chlaenius sericeus (Forster, 1771)	1	0.04	2	0.07	—	—	4	0.11	7	0.05
Bembidion coloradense Hayward, 1897	—	—	—	—	5	0.14	—	—	5	0.04
Amara confusa LeConte, 1848	—	—	1	0.03	2	0.06	2	0.05	5	0.04
Clivina fossor (Linné, 1758)	—	—	1	0.03	3	0.09	1	0.03	5	0.04

Bembidion rapidum (LeConte, 1848)	—	—	1	0.03	—	—	4	0.11	5	0.04
Harpalus somnulentus Dejean, 1829	—	—	—	—	3	0.09	2	0.05	5	0.04
Amara ellipsis (Casey, 1918)	—	—	1	0.03	3	0.09	—	—	4	0.03
Bembidion scudderi LeConte, 1878	—	—	—	—	1	0.03	3	0.08	4	0.03
Axinopalpus biplagiatus (Dejean, 1825)	—	—	—	—	3	0.09	—	—	3	0.02
Piosoma setosum LeConte, 1848	—	—	—	—	1	0.03	2	0.05	3	0.02
Bembidion acutifrons LeConte, 1879	—	—	1	0.03	1	0.03	—	—	2	0.02
Cymindis cribricollis Dejean, 1831	1	0.04	—	—	—	—	1	0.03	2	0.02
Harpalus nigritarsis Sahlberg, 1827	—	—	—	—	2	0.06	—	—	2	0.02
Cymindis borealis LeConte, 1863	1	0.04	—	—	—	0.00	—	—	1	0.01
Bembidion concolor (Kirby, 1837)	—	—	—	—	1	0.03	—	—	1	0.01
Amara convexa LeConte, 1848	—	—	—	—	—	—	1	0.03	1	0.01
Amara cupreolata Putzeys, 1866	—	—	—	—	—	—	1	0.03	1	0.01
Amara discors Kirby, 1837	1	0.04	—	—	—	—	—	—	1	0.01
Passimachus elongatus LeConte, 1846	—	—	—	—	1	0.03	—	—	1	0.01
Elaphrus lecontei Crotch, 1876	1	0.04	—	—	—	—	—	—	1	0.01
Badister neopulchellus Lindroth, 1954	1	0.04	—	—	—	—	—	—	1	0.01
Bembidion nudipenne Lindroth, 1963	1	0.04	—	—	—	—	—	—	1	0.01
Diplocheila oregona (Hatch, 1951)	—	—	—	—	1	0.03	—	—	1	0.01
Loricera pilicornis (Fabricius, 1775)	—	—	1	0.03	—	—	—	—	1	0.01
Lebia vittata (Fabricius, 1777)	1	0.04	—	—	—	—	—	—	1	0.01
Total Carabids	2608		3004		3496		3705		12813	

Appendix 3: Mean diversity indices for each treatment for each year (n = 4, S.E except potato plots in 2005 where n = 3).

2000	Species Richness	Average Species Richness	Average Shannon-Wiener H'	Average Evenness J'
Bean Conventional	22	13.8 ± 1.1	1.88 ± 0.08	0.74 ± 0.05
Bean Sustainable	24	14.0 ± 1.0	1.66 ± 0.25	0.64 ± 0.10
Potato Conventional	18	9.8 ± 2.0	1.32 ± 0.28	0.59 ± 0.10
Potato Sustainable	14	9.8 ± 0.5	1.44 ± 0.16	0.63 ± 0.06
Wheat Conventional	18	11.5 ± 0.6	1.84 ± 0.17	0.77 ± 0.08
Wheat Sustainable	19	10.3 ± 1.7	1.41 ± 0.25	0.62 ± 0.09
2003				
Bean Conventional	25	12.5 ± 1.5	1.64 ± 0.18	0.66 ± 0.05
Bean Sustainable	32	18.5 ± 2.3	1.87 ± 0.17	0.65 ± 0.07
Potato Conventional	24	11.5 ± 2.1	1.84 ± 0.18	0.77 ± 0.04
Potato Sustainable	24	12.3 ± 0.8	2.12 ± 0.06	0.84 ± 0.01
Wheat Conventional	24	12.3 ± 2.3	1.45 ± 0.38	0.59 ± 0.09
Wheat Sustainable	28	15.0 ± 2.5	1.64 ± 0.11	0.62 ± 0.03
2004				
Bean Conventional	29	16.0 ± 0.4	1.89 ± 0.18	0.69 ± 0.06
Bean Sustainable	30	19.5 ± 1.0	1.89 ± 0.23	0.64 ± 0.07
Potato Conventional	30	16.8 ± 2.3	2.38 ± 0.06	0.87 ± 0.03
Potato Sustainable	32	18.25 ± 1.1	2.19 ± 0.16	0.77 ± 0.05
Wheat Conventional	33	19.8 ± 1.9	2.08 ± 0.2	0.71 ± 0.05
Wheat Sustainable	33	20.25 ± 2.2	2.25 ± 0.15	0.75 ± 0.05
2005				
Bean Conventional	28	16.0 ± 0.7	1.88 ± 0.11	0.69 ± 0.04
Bean Sustainable	24	13.5 ± 0.8	0.96 ± 0.07	0.37 ± 0.04
Potato Conventional	24	15.0 ± 1.2	1.78 ± 0.15	0.67 ± 0.04
Potato Sustainable	24	15.0 ± 1.3	1.78 ± 0.11	0.66 ± 0.05
Wheat Conventional	33	17.0 ± 1.2	1.54 ± 0.31	0.55 ± 0.11
Wheat Sustainable	32	17.8 ± 1.4	1.41 ± 0.28	0.49 ± 0.09

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4. Chapter 4: General Discussion

I investigated the impact of several farming practices on carabid assemblages in southern Alberta. My results are consistent with those from other studies in demonstrating that farming practices can affect the activity density, diversity and species composition of carabid assemblages (Kromp 1999). In Chapter Two I assessed the effect farming practices associated with genetically modified herbicide tolerant (GMHT) corn variety and in chapter three I investigated the effect of several contemporary "sustainable" farming practices (1- organic fertilizer, 2- reduced or no tillage, 3- straight cutting of solid seeded beans and 4- fall seeded cover crop) on carabid assemblages. Considering the relatively large carabid assemblage studied and the vast range of biological requirements generally representative of such groups of carabid species (Thiele 1977), my study underscores that species level analyses are important for fully understanding the effect of farming practices on the carabid assemblages. Without species level analysis one may reach erroneous conclusions regarding insect pest management. For instance, increasing population size of seed-eating carabids cannot benefit insect pest management program. However, it may play a role in weed management. Fuller understanding will help us to more effectively meet our objectives.

4.1. Thesis summary

As shown in chapter two, carabids showed only minor responses to GMHT corn, although many species responded to the difference in weed density between the two varieties. For example, in the first year, activity of many small carabids like *Bembidion quadrimaculatum*, was higher in conventional corn than in the GMHT variety, apparently in response to a strong emergence of redroot pigweed in GMHT corn in mid season. Brooks et al. (2003) also reported lower activity density of *Bembidion* species in GMHT crops.

Additionally, I investigated the effect of rotating canola with corn on carabid assemblages. Rotation seemed to strongly influence both diversity and activity density. In fact, diversity was reduced in corn under rotation but the overall activity density was enhanced. This is contrary to findings of Lövei (1984), who reported a higher diversity in corn under rotation, but similar to results of Brust et al. (1986) who reported an increase in abundance under rotation. In one year, phytophagous carabids, particularly *Amara farcta*, appeared to be attracted to the residual canola seeds in the rotation treatments. Additionally, my results suggest that weed density influences carabids differently, depending on their body size. Higher numbers of small-bodied species were collected under low weed density while the opposite was observed for large-bodied carabids.

In the third chapter, I demonstrated that sustainable practices positively influenced the activity density of carabids, but had no significant effect on their diversity Many previous studies have also reported higher carabid activity density under organic and/or sustainable farming regimes (Dritschilo and Wanner 1980, Kromp 1989, Fan et al. 1993, Pfiffner and Niggli 1996) and a few have shown no effect on diversity (Clark 1999, Melnychuk et al. 2003). Species such as *Amara farcta* and *Bembidion quadrimaculatum* responded strongly to sustainable wheat and conventional beans respectively. Additionally, many species showed a preference for a particular crop. For example, activity density of *Poecilus corvus* and *Agonum placidum* were enhanced in wheat plots.

Application of insecticide as required in potato plots may explain the decreased activity density of carabids in this crop each year. This is consistent with other studies showing the toxic effect of insecticides on non-target carabids (Mowat and Coaker 1967, Edwards and Thompson 1975, Sekulic et al. 1987). Species composition was greatly influenced by crop type but the influence of treatment was less important. Similarly, populations of adult click beetles were also greater in the sustainable treatments, probably resulting from the lack of tillage and the application of manure. Also, wheat seemed to be favoured by adult click beetles (Doane et al. 1975, Vernon et al. 2000). Overall, the third chapter shows that crop type, inputs (sustainable or conventional) and their interaction can influence the distribution of certain more specialized carabid species but not that of habitat generalist species like *Pterostichus melanarius*. Additionally, this study reinforces the conclusion that it is possible to detect responses of carabid beetles to treatments using small plot size (i.e. *c*. 8 m by 10 m). Butts et al. (Butts et al. 2003) argued that the effects of treatment on carabids, when studied in small plot can be masked by interplot movements, despite many demonstrations of significant impacts in studies using small plots (Clark et al. 1993, Cárcamo and Spence 1994, Honek 1997) .

4.2. Implication for agriculture

As stated previously, some carabid beetles prey on many arthropod pests as well as weed seeds, and consequently, their role in reducing risk of pest outbreak is potentially important. Evidence of significant carabid predation on agricultural pests is numerous (Brust et al. 1985, Chiverton 1988, Grafius and Warner 1989, Floate et al. 1990, Menalled et al. 1999). Intuitively, farming practices that negatively affect carabid population size will reduce efficiency of the beetles in removing pests from the field. Overall, the use of GMHT corn variety did not affect the carabid assemblages, although a few particular species were affected. Weeds within a field seem to be an important component of the overall habitat requirement of many carabid species and therefore, it may well be possible to manipulate weed density to increase predator density (Altieri and Whitcomb 1979, Barney et al. 1984). Moderate weed density within a field will not only provide a more suitable habitat for most carabid species but can also reduce crop damage by providing alternative food for phytophagous insects, which in turn reduce crop damage. In fact, oviposition by root maggots (Diptera: Anthomyiidae) was reduced in weedier crop caused by delayed herbicide application (Dosdall et al. 2003). Such effects could depend on predation by carabids.

Sustainable agricultural practices, as described in Chapter Three, seemed to promote carabid population density, which in turn should increase predation rate on potential pests. Application of manure and no till regime were most likely the farming practices responsible for this increase as shown by other studies (House and Stinner 1983, Ferguson and McPherson 1985, Hance and Gregoire-Wibo 1987, Humphreys and Mowat 1994, Andersen 1999). On the other hand, populations of adult click beetles were also enhanced by those practices and this might translate into higher crop damage. However, only the distribution of the adult click beetles was monitored and caution should be used when extrapolating the consequences of sustainable farming on wireworm distribution. Intuitively, a higher adult click beetle abundance will translate into higher larval abundance. However, very little is known about interaction between carabid and click beetle communities but one might expect some predation of carabid larvae and adults on juvenile elaterids.

4.3. Future Research and Improvements

Although the probable positive impact of increasing carabid population size within a field in relation to reducing pest outbreak is well accepted, very few studies have demonstrated an economic return for this concept (Snyder and Wise 1999). Most of what is known about the services provided by carabids is in relation to their efficiency in removing pests from fields (Hance 1987, Grafius and Warner 1989, Menalled et al. 1999) but this is rarely linked to concepts like economic threshold. It is difficult to evaluate the role of carabids alone as many factors interact in an agroecosystem and these cannot not be easily measured. As a result, direct cause and effect is difficult to demonstrate. However, to promote certain farming practices that enhance the carabid communities, demonstration of economic benefit should be a priority. Manipulation studies where community of carabids are enhanced, reduced or natural should be performed to test for economical benefits.

Concerning other studies of carabids in agroecosystems, better monitoring of abiotic and biotic factors potentially influencing beetle assemblages should be emphasised. Farming practices are likely to influence soil temperature, physical properties, moisture and weed density and these, in turn, influence carabid distribution. Also, it is clear that intra- and interspecific competition influence the distribution and abundance of species, but this dimension is seldom considered when studying the carabids in agroecosystems. Prasad and Snyder (2004) suggested that increasing the activity density of large carabids can reduce the activity density of small carabids through intraguild predation. Nonetheless, their study showed that predatora can significantly influence the population size of aphids despite intraguild interference (Prasad and Snyder 2004). Interference of biocontrol agents such as carabids or wolf spiders potentially reducing their efficacy was also suggested in other studies (Snyder and Wise 1999, Lang 2003). A better monitoring and understanding of the influence that the biotic and abiotic factors have on the population of beneficial arthropods will increase our chances to develop farming strategies that will enhance their beneficial actions and promote the sustainability of agriculture

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